

UNIVERSIDADE DE LISBOA
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Retrofitting and refurbishment processes of heritage buildings: application to three case studies

Sara Lúcia Gonçalves de Almeida

Dissertação de Mestrado Integrado em Engenharia da Energia e do Ambiente

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Abstract

Buildings in Europe represent 40% of total energy consumption and 36% of Greenhouse Gas Emissions. This research focuses in heritage buildings. These represent the legacy of a society that is inherited from past generations, maintained in the present and given for the benefit of future generations.

This research was part of the European project Reducing Footprints of Monumental Structures, Landscapes and Buildings (ReFoMo) that explored the potential and demand for retrofitting and refurbishment projects which will improve the energy efficiency of heritage buildings. For this, an extensive literature review was performed in order to find the solutions already implemented in this type of buildings. Then, a comparative analysis of three case studies was executed – three buildings in countries partners of the project. By merging what was learned both from literature review and from the case studies, it was recognised what failed and the good examples. Therefore, it is suggested as the basis of a framework: i) creation of a multidisciplinary team; ii) performance of an energy audit, iii) careful analysis of the existing solutions for each specific case and; iv) elaboration of a maintenance plan after implementing measures aiming at control the benefits of the implementation in long terms conditions. This framework will improve the energy performance of heritage buildings when applied.

Keywords: heritage buildings, energy efficiency, retrofitting, refurbishment.

Resumo

Na Europa, os edifícios são responsáveis por 40% do consumo energético total e por 36% das emissões de gases de efeito de estufa. Este trabalho focou-se nos edifícios de património. Estes edifícios são aqueles que representam o legado de uma sociedade, herdado de gerações passadas, mantido no presente e entregue para o benefício das gerações futuras.

Este trabalho fez parte do projecto europeu Reducing Footprints of Monumental Structures, Landscapes and Buildings (ReFoMo) que explorou o potencial e as necessidades de projectos de adaptação e renovação que visavam melhorar o desempenho energético de edifícios de património. Para isso, realizou-se uma extensa revisão bibliográfica a fim de encontrar as soluções já implementadas neste tipo de edifícios. Posteriormente, realizou-se uma análise comparativa dos três casos de estudo – três edifícios em países parceiros do projecto. Ao confluir o que foi aprendido da revisão bibliográfica e dos casos de estudo, foram detectadas as falhas e os exemplos a seguir. Portanto, sugere-se como um plano a seguir: i) a criação de uma equipa multidisciplinar; ii) a realização de uma auditoria energética prévia, iii) a análise cuidadosa das soluções existentes para cada caso específico e; iv) a elaboração de um plano de manutenção de controlo dos benefícios após implementação das medidas que melhoram o desempenho energético dos edifícios. O desempenho energético dos edifícios do património será melhorado sempre que esta metodologia for aplicada.

Palavras-chave: edifícios de património, eficiência energética, adaptação, renovação.

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1 Introduction

1.1 Research background

According to the Buildings Performance Institute Europe (BPIE, 2011), buildings in Europe represent a large share in the total energy consumption (40%) and Greenhouse Gas Emissions (36%). Currently, international communities are making a large compromise to increase their energy efficiency. The EU document *Europe 2020 A European strategy for smart, sustainable and inclusive growth* proposes to reduce the Greenhouse Gas Emissions (GGE) targets in 20% comparatively to 1990 levels and increase the use of renewable sources to achieve 20% of total energy production and level up energy efficiency by 20%. This strategy has been recently stressed in the Communication on the 2030 policy framework. These documents reflect the EU's goal of reducing GGE by 80-95% below 1990 levels by 2050 as part of the effort needed from developed countries (EU COM, 2014).

The European building stock with its unique mix of heritage provides significant opportunities and challenges. There are three main types of heritage according to UNESCO: cultural, natural and heritage in the event of armed conflict. The first one can be tangible such as paintings, monuments or shipwrecks, or intangible such as oral traditions or rituals. Natural heritage includes natural sites with cultural aspects such as landscapes, physical, biological or geological formations. The concept of heritage in the event of armed conflict emerged from The Convention for the Protection of Cultural Property in the Event of Armed Conflict as a consequence to the massive destruction of the cultural heritage in the Second World War. It covers immovable and movable cultural heritage, including monuments of architecture, art or history, archaeological sites, works of art. Summarizing, heritage is the legacy of a society that is inherited from past generations, maintained in the present and given for the benefit of future generations.

The cultural heritage sector is among the most important European attractors and economic drivers. It generates millions of jobs and is essential to the 3 economic sectors which contribute most to EU GDP; the Cultural and Creative industries, the Real Estate activities and the Tourism industry (Nypan, 2009). Heritage buildings reflect both the unique character and identity of European cities but include essential infrastructure for housing or public buildings. These buildings were constructed without much energy efficiency interests and show high energy consumption levels. For example the heating energy demand of a building built after 1990 is around 40 kWh/m² while buildings built before 1930 demand 170 kWh/m² (Balaras, 2004). Since this sector is so relevant, improving energy efficiency in cultural heritage buildings through refurbishment techniques will contribute to a growing economy. Due to the need to preserve authenticity and integrity, many recently developed solutions in the field of renovation are not compatible with or adequately adapted for use in historic buildings (EC, 2013). Their energy performance, conservation and retrofitting systems must be studied with the thought of keeping their material and immaterial values. According to the Energy Efficiency Directive (EED, 2012/27/EU) adopted in October 2012, member States shall establish a long term strategy for mobilising investment in the renovation of national stock of residential and commercial buildings, both public and private. Furthermore the Directive includes a requirement to develop long term renovation strategies for national building stocks such as to

renovate 3% of total floor area per year. Undertaking sustainable energy renovation of buildings can have economical, societal and environmental benefits.

Heritage buildings are defined as buildings built before 1945 having an historic, monumental or iconic importance for the city (Heritage Canada Foundation, 2003). Representing 10% of the total Europe's built stock, these buildings have very different and complex physical functioning due to their design and structure. Refurbishment of only half of Europe's heritage buildings with an average of factor 4 (i.e. to 25% of the demand before the intervention) reduction will result in a reduction of 5,6% of the total energy demand of buildings representing 2,25% of the total energy consumption (Climate-KIC, 2013). The reason for intervention in heritage buildings is to improve their conservation status, comfort and energy conditions for their better use and exploitation, therefore demanding a special approach because of their lack of adaptation to the modern world. Due to high thermal comfort in modern day buildings, higher requirements are being set for heritage building (Schellen, 2002). The purposes of today and possibilities as conference rooms, hotels and libraries require refurbishment and/or retrofitting processes. Their renovation implies a careful and effective study among the retrofitting possibilities without removing cultural and patrimonial value. These buildings are architectural icons of a city and must be preserved.

The refurbishment of buildings provides excellent opportunities to reduce energy consumption in buildings (Mickaitylė et al., 2008). When working on existing buildings to improve their environmental performance, refurbishment is seen as an opportunity to exploit renewable sources and related technologies, emphasizing passive and active solar energy solutions, day lightning, natural cooling, cogeneration of heat and power and connection to district heating (Balaras et al., 2005). An example of a heritage building benefited by retrofitting is the Bernardas' Covent in Lisbon (Martins & Carlos, 2013). The study analysed how the replacement of individual components such as windows, glazing, vertical walls and roofs, can favour an energy performance adjustment. Over the last years, different European projects have focused on heritage buildings refurbishment, for example the FP7 project New4Old - New Energy for Old buildings Integration of RUE and RES in Old buildings and the IEE project 3ENCULT- Efficient Energy for EU Cultural Heritage. These projects focused on the integration of renewable energy sources into heritage buildings and rational use of energy. They also showed that reducing energy demand depends on the case and the heritage value. However, all these projects were focused on the refurbishment of a specific building. Projects like New4Old and 3ENCULT allow comparisons to similar buildings as the ones studied within this research (Lollini, 2010). They challenged this research to go further investigating how the refurbishment and retrofitting systems already in use can be applied in different European settings.

1.2 Problem definition

Heritage buildings present a low energy performance and to maintain their conservation, to turn them more comfortable and to lower the consumption, refurbishment is the solution. Nevertheless, it is important to ensure that historic properties are comfortable and suitable for contemporary lifestyles. Therefore their consequent refurbishment has a large potential. The present research aimed at analysing the existing solutions, condensate them and find those that can be applied in different conditions. Although it is acknowledged that each heritage building

is unique and therefore it needs customized energy solutions, this research aimed at finding which standards and tools can be considered universal. It also aimed at understanding if different technologies and solutions are applicable under different circumstances. Guidelines are suggested to try to refurbish heritage buildings on a standardized way. These guidelines are the basis for a framework ready to apply in heritage buildings at European level. Hence, this research formulated the following research question: “How to improve the energy performance of heritage buildings?”

To answer the main research question, the following sub-questions were also formulated:

- 1) What are the important elements of an energy audit to be conducted in buildings?

Diagnostic and monitoring tools, for example thermal imaging or wireless sensors, allowed analysing the building performance and, as a consequence, finding where the energy saving opportunities were.

- 2) How can an energy audit be customized for use into heritage buildings?

Improving energy efficiency standards in heritage buildings can be particularly complex because many of the solutions that apply to modern buildings cannot be applied to older properties. Therefore to find which standards and tools can be considered universal, this question was mandatory.

- 3) What refurbishment techniques are available and suitable for heritage buildings?

To be able to look for the solutions applicable in heritage buildings, the techniques available had to be first encountered and studied. Answers for the first and second sub-questions provided the information required to build step by step a plan for refurbishment of heritage buildings (for example rules of thumb, do's & don'ts, schemes).

- 4) What are the main factors to take into account while aiming at refurbishing heritage buildings?

The availability of technologies is important yet not sufficient. It was also necessary to understand how to apply different technologies and solutions under different circumstances (i.e. use, location and climatic conditions).

1.3 Relevance

This research was part of the European project Reducing Footprints of Monumental Structures, Landscapes and Buildings. ReFoMo explored the potential and demand for restoration projects which would improve the energy efficiency of heritage buildings. ReFoMo is an effort of three countries. The sample refers to: i) fortresses in Utrecht (Netherlands), ii) a historic building working as the Faculty of Engineering in Bologna (Italy); iii) an industrial gas production building in Budapest (Hungary). The present master thesis research had societal relevance since it provided information to ReFoMo.

Thus, through a wide range of analysis, this master thesis discusses the refurbishment possibilities that a building considered heritage building has and the outcome, ideal and realistic, as a factor of growth and cultural development. The framework generated constitutes a confluence of ideas and techniques giving a new kind of integrity to renovation processes. The

outcome of the research was expected to improve the current status of refurbishment and retrofitting of historic buildings sector.

1.4 Structure of the Master Thesis

This Master Thesis is divided into seven chapters as Figure 1 shows. Chapter 2 is Heritage buildings and describes the different functional characteristics between heritage and modern buildings. It explains why these buildings are so important to preserve and to refurbish instead of leaving them abandoned. Chapter 3 is Refurbishment and retrofitting: an overview. It reflects three distinct phases. First, presents diagnostic and monitoring tools available for energy performance evaluations. Secondly, a customized energy audit for heritage buildings is suggested. Then, an extensive literature review concerning a great part of measures applied on other heritage buildings, retrofitting and refurbishments systems are assessed. Previous studies and projects, personal exchanges *in situ* and interviews with experts allowed listing refurbishment and retrofitting systems already in use, their options and challenges to be explored. Methods is chapter 4 and explains the methods followed to answer the research question. Chapter 5 presents the Results through a comparative analysis on the three case studies. It is discussed which solutions can be found similarly in the three case studies and in the literature. Chapter 6 discusses the findings of this research, namely the suggestions in order to perform an energy efficient retrofitting for heritage buildings. The final chapter gives concrete answer to the research questions. Also, the limitations of the study and indications for further research are presented.

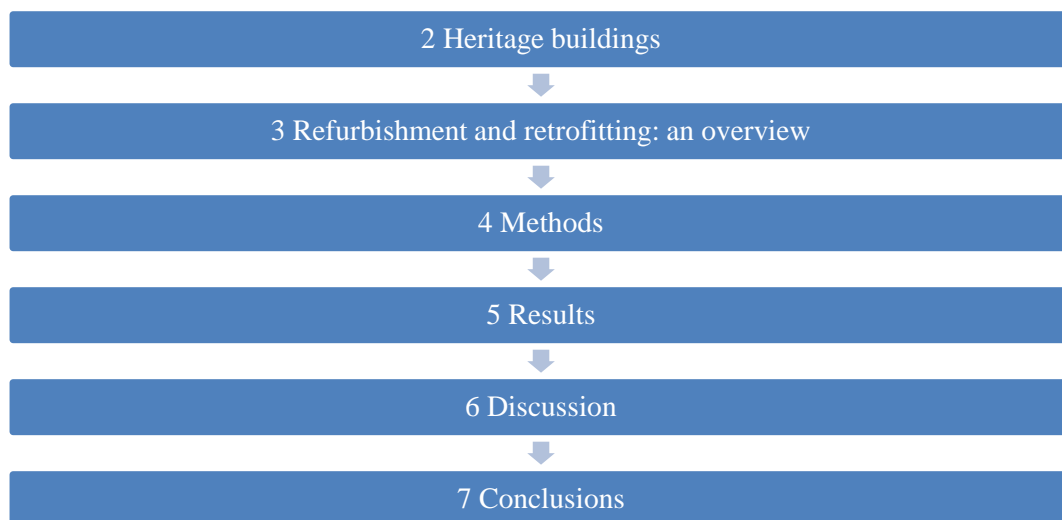


Figure 1 - Structure of the report

2 Heritage buildings

According to BP (2014), global primary energy use increased by 2,3% in 2013, an acceleration over 2012 of 1,8%. Growth in 2013 speeded up for oil, coal and nuclear power but global growth remained below the 10-year average of 2,5% (BP, 2014). This world trend of growing energy use raised concerns about supply difficulties, depletion of energy resources and heavy environmental impacts. According to the Buildings Performance Institute Europe (BPIE, 2011), buildings in Europe represent nowadays a large share in this total energy demand (40%) and Greenhouse Gas Emissions (36%). Different buildings require different amounts of energy to maintain the same level of comfort to work or live in. The amount of energy a building uses is determined by a number of factors that vary according to geography, climate, building type and location. Krarti (2000) went deeper specifying these factors including:

- i) Purpose of building;
- ii) Size of building;
- iii) Efficiency of building equipment and systems;
- iv) Number of people in a building and its hours of operation;
- v) Operation and maintenance practices;
- vi) Age and construction characteristics of a building.

A building built after 1990 uses around 40kWh/m² while buildings built before 1930, which are considered heritage buildings, demand 170kWh/m² demand (Balaras, 2004). The retention of historic buildings and the principles of sustainability are not that far from each other (English Heritage, 2012). Finding solutions compatible with conservation enhances therefore long term preservation and sustainable management of our towns.

2.1 Characteristics of heritage buildings

It is vital to understand that historic buildings are a finite resource and that in their existence there is not only embodied energy¹ and carbon but the spirit and identity of a country. Likewise in the drive towards sustainable design it should be ensured that local distinctiveness and character is retained. Care must be taken to achieve a balance between work to bring an old building up to modern performance standards and sustainability requirements (Godwin, 2011). Achieving a low carbon and, consequently, an energy efficient city requires a holistic consideration on the economic, social, environmental and the political concerns which constitute the four fundamental pillars in a solid sustainability framework (Yung & Chan, 2012).

A building of historic interest generally shows examples of design, building techniques or materials that inform contemporary and prospect developments. One of the most important thought in terms of building conservation is to retain the original fabric, when it still exists, and character of historic buildings. Optimising the existing historic building energy performance of

¹ Embodied energy is the energy consumed by all of the processes associated with the production of a building. This includes the mining and manufacturing of materials and equipment, transportation of materials and administrative functions (Heritage Council of Victoria, 2009).

heritage buildings may assist in achieving energy efficiencies and broader sustainability objectives. Nineteenth and some early twentieth century masonry buildings, for example, have very different functional characteristics than more modern buildings with their contemporary moisture barriers, damp-proof courses, membranes, cavity walls and insulation (Heritage Council of Victoria, 2009).

One of the most different functional characteristics between heritage and modern buildings is their ability to breathe². Modern buildings often require mechanical ventilation. On the other hand, heritage buildings of masonry construction or buildings with timber floors were designed to allow natural ventilation to reduce dampness. These features make them more porous and naturally ventilated, so they breathe more. They generally include soft and permeable materials that respond to air and moisture very differently to many of the hard impermeable materials used in modern buildings. The ventilation of historic buildings makes them less predisposed to condensation and its associated effects (Change Works, 2008).

Figure 2 shows moisture, air movement and thermal performance of a historic building (a) and a modern building (b). Historic buildings present more sources of heat transfer through porous and permeable walls, ventilation through open flue and open fire and also from below floor. There are heat losses due to fabric characteristics and limited solar gain caused by small openings and massive walls. Modern buildings show a sealed envelope which reduces air infiltration and moisture from ground, creates vapour barriers and limits heat loss. Additionally solar gain increases within well-insulated fabric. Over-sealing historic buildings can cause considerable problems in terms of condensation and other associated problems. In addition, in rooms where there is a gas or solid fuel burning appliance, it is crucial to have adequate ventilation as a safety requirement (Change Works, 2008).

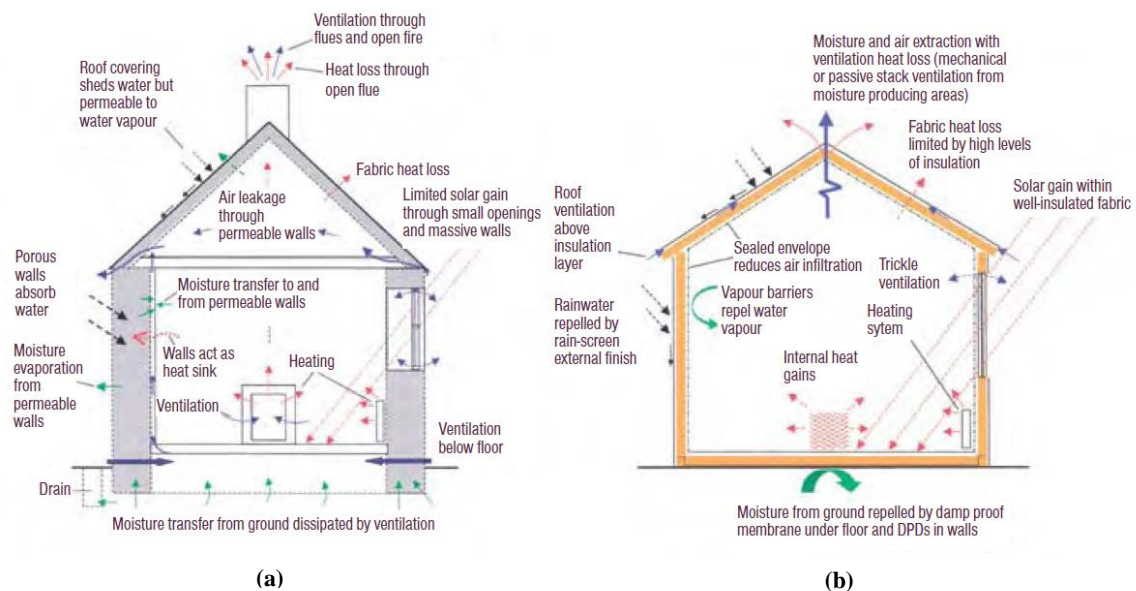


Figure 2 - Historic (a) and modern (b) buildings functioning (source: Change Works, 2008)

² Breathing is the ability of historic buildings to control moisture within the building fabric to evaporate freely away and potential long-term decay problems. It also enables provision of high quality indoor environments and uses less energy (English Heritage, 2012).

Following the need to breathe that historic buildings have, they can often be draughty and leak heat. Larger window sizes and predominance of sash and case windows provide a greater area of low-efficiency glazing and more potential for draughts (Change Works, 2008).

Historic buildings often have larger rooms with higher ceilings, which need more energy to keep them warm. Without proper insulation, internal heat gains are easier to leak. Many older building components have lower levels of thermal efficiency and heating systems tend to use more energy generating less heat when compared to modern materials and systems (Change Works, 2008). These buildings also perform differently from a thermal point of view in comparison with modern buildings. Heritage buildings traditionally built of masonry and stone are described as being thermally heavy or having high thermal mass due to massive and thick walls. In other words, these buildings present the ability to absorb heat in high temperatures and release it when temperatures fall (Godwin, 2011). This ability is measured through thermal transmittance, also known as the heat transfer coefficient and “U” value, a number that expresses how quickly heat passes through a material. The “U” value is a measure of heat loss in a building element such as a wall, floor or roof. It can also be referred to as an overall heat transfer coefficient since it indicates how well heat is transferred through the different parts of a building. The higher the “U” value, the greater will be the heat losses. Therefore, worse the thermal performance of the building envelope. A low “U” value usually indicates high levels of insulation. They are useful as it is a way of predicting the composite behaviour of an entire building element rather than relying on the properties of individual materials (U-Values, 2014). Table 1 shows “U” values for some of the materials typically used in building construction (Change Works, 2008). These values allow for relatively easy identification of areas most prone to heat loss. Traditional buildings in the UK and Europe, due to their heavy thermal mass can stay cooler due to their construction and being thermally heavy. This effect might be useful for night ventilation in regions with hot summer climate. On the other hand, in case of temporary use of the building during the heating season, high thermal inertia is counterproductive for fast heating of the rooms. Internal insulation decouples the thermal capacity of the wall from the room air, which is good in terms of temporary use, but counterproductive in terms of night ventilation cooling (Rainer & Baldracchi, 2011).

Table 1 - “U” values of typical heritage building component (source: Change Works, 2008)

Building component	“U” value $\left[\frac{W}{m^2K}\right]$
Window: timber frame, single glazing	4.8
Window: uPVC frame, double glazing	2.0
Solid brick wall	2.1
Solid sandstone wall (pre-1900 to 1966, 600mmm)	2.1
Brick cavity wall (1900 to 1975), uninsulated	1.6
Brick cavity wall (1900 to 1975), insulated	0.5
Pitched roof, uninsulated	2.3
Pitched roof, insulated (250mm)	0.16
Suspended timber ground floor, uninsulated	0.64
Solid ground floor, uninsulated	0.43

Heritage buildings are under a significant pressure to reduce carbon emissions. This revolves around energy conservation and efficiency of buildings. These buildings require refurbishment

processes and the challenge is how to achieve it without damaging the intrinsic architectural or historic character and significance of a building and structure. Therefore a balance between making alterations to improve efficiency and safeguarding the special architectural and historic interest of a building needs to be taking into account (Godwin, 2011). Otherwise lasting damage could be inflicted and its significance diminished.

2.2 Purpose to refurbish heritage buildings

The notion of preserving what exists and making the maximum use of it fits well with the aims of building conservation. The criterion to this is the fact that the historic buildings are a finite and precious resource (Godwin, 2011). The concept of conservation is preserving the authenticity of the heritage based on the original historic evidence (Harun, 2011). The United Kingdom Guidance for Practice defines conservation as “the means by which the true nature of an object is preserved” (UKIC, 1983). Furthermore it is stated that the distinctiveness of an object “includes evidence of its origins, original construction and the materials of which it is composed and information as the technology used in manufacture”. Design and materials included the architecture and construction technique is considered to be an important value in a building because it brings together the history of the past. In these original design and materials, it is contained evidence of knowledge which has been gone with time, ideas and the golden era of the heritage buildings (Harun, 2011). Moreover Harun (2011) sustains that building conservation is a multi-disciplinary field which involves inputs from various professionals including architects, engineers, historians, archaeologists, chemists, environmentalists, and other experts.

The purposes and possibilities of today that heritage buildings represent, work as an impetus and inspiration for their conservation and maintenance. Therefore, their new uses are one of the reasons why heritage buildings are refurbished, i.e. being restored to its former good condition. According to Power (2008) some of the benefits offered by refurbishment are among the following:

- Renovation preserves the basic structure of the property and retains existing infrastructure in an existing built environment;
- The renewal of a building has an immediate beneficial effect on neighbouring properties because it gives a clear signal that the neighbourhood is worth investing in;
- Upgrading is far quicker than demolition and replacement building because, in most cases, it involves adaptation of the existing structure and layout of a building rather than starting from scratch;
- It is less disruptive because even where major work is undertaken, unless a dangerous structure is involved, people can usually stay inside and the area services continue to operate;
- It involves a shorter and more continuous building process since most of the work can happen under cover in weatherproof conditions. Compared to new build, this involves many months of exposure to all weathers while building the foundations and main structure;

- It has a positive impact on the wider neighbourhood sending a signal that renewal and reinvestment will ensure the long term value and stability of an area. This, in turn, generates other investments and a broader upgrading;
- Older existing buildings require constant upgrading. Renovation has a positive effect on street conditions, social mixing, service quality, local transport and schools, since it adds value and attractiveness.

Adaptation is a method of extending the useful life of buildings by a combination of improvement and conversion (Kohler & Hassler, 2002). This adaptation combined with the energy savings, carbon emissions reduction, and the social and economic advantages of recycling a valued heritage building, makes adaptation turns into the reuse of a building which is an essential component of sustainable development (Department of the Environment and Heritage, 2004). Adaptive reuse of historic buildings, i.e. changing the original purpose of a heritage building to suit new conditions or needs and so reusing it, has a major importance in the sustainable development of communities, avoiding the processes of demolition and reconstruction. This alone sells the benefits of adaptive reuse (Department of Environment and Heritage, 2004). Figure 3 shows an example of adaptive reuse: The Béthanie historic building complex was built in 1875 as a sanatorium. The complex was allocated in 2003 to the Hong Kong Academy for Performing Arts and reopened in 2006 (Yung & Chan, 2012). Reuse can create valuable community resources from unproductive property, substantially reduce land acquisition and construction costs, revitalize existing neighbourhoods and help control sprawl (Bullen, 2007). In particular, extending the life of an existing building through reuse can lower material, transport and energy consumption and pollution and thus make a significant contribution to carbon emissions reduction and sustainability (Bullen, 2007). Adapting and refurbishing heritage buildings to suit new applications is an effective strategy; besides extending the life cycle of a building, it reduces its carbon emissions and improve cost efficiency, but also conserve significant heritage values (Yung & Chan, 2012).



Figure 3 - Bethanie Chapel adapted to an Academy for performing arts in Hong Kong (source: Yung & Chan, 2012)

The growing perception that old historic buildings are often cheaper to convert to new uses than to demolish and rebuild is one of the reasons for the interest in adaptation and furthermore their refurbishment (Bullen, 2007). The existing built environment contains significant amounts of embodied energy. With appropriate modification, properly managed traditional built structures

will last and play an important part in the conservation of energy and control over carbon emissions both now and in the future. So by keeping existing structures and buildings a contribution and a reduction in energy use is already achieved. Accordingly to Godwin (2011), by retaining and re-using original materials wherever these are available and making use of the embodied energy of those materials rather than wasting it is a substantial contribution to the goal of achieving sustainable development. Also the energy expended in the fabrication of materials and their transporting together with the construction of a new building is often equal to the energy used to service the energy requirements of a new building for up to 10 years (Godwin, 2011). Giving a new use to historic buildings will minimise the consumption of greenhouse gases and energy used in demolition. Additionally heritage buildings - when refurbished - will provide more comfort, a reduction of primary energy demand and therefore an improvement of energy efficiency.

The refurbishment of these large amount of European buildings, improves several conditions of a building namely its exploitation, noise insulation conditions which prolongs buildings life cycle and increases the value of the building (Mickaitytė et al., 2008). It is important to ensure that heritage buildings are comfortable, affordable and suited to contemporary lifestyles (Change Works, 2008). Based on the factors affecting energy consumption of a building mentioned, it is important to view these historic building energy uses in context with the function, use, and characteristics of each building. Energy savings can be achieved from virtually all buildings, through improvements in tasks or energy efficient retrofitting of building components (i.e. lights, windows, heating and cooling equipment.). In addition, historic buildings need to be adapted to cope with worse weather, higher temperatures and increased flood risk as climate change takes effect (Roberts, 2008).

3 Refurbishment and retrofitting: an overview

Over the past 40 years, energy efficiency improvements focused on increasing efficiency of every kind of end use system such as buildings, appliances, vehicles and industrial operations. In the 1970s, the reason for researching conservation of energy was the energy crisis, raising concern about a possible depletion of fossil fuels. In the beginning of XXI century, environmental problems – global warming – were the main reasons to impulse energy conservation (Abrahamse et al., 2005).

According to the Buildings Performance Institute Europe (BPIE, 2011), the share of total energy consumption in the most relevant economic sectors is as follows: buildings represents 40%, followed by transport with 33%, industry 24% and finally agriculture with 2%. In the case of the building sector, significant investments are being made to reduce energy consumption through weatherization, energy auditing and retrofitting strategies (Krarti, 2011). Heritage represents 10% of the total European building stock (Climate-KIC, 2013). The fabric and design of a heritage building add an exclusive identity to a city creating a focal point that people can relate to. It is a resource that can play an important role in the future of towns, cities and rural areas in terms of the stimulus to regeneration and the promotion of sustainable development (English heritage, 2013b). The stock of historic buildings is finite and every loss or major alteration to fabric is significant. A conservative approach is therefore needed – one in which knowledge and experience are used to determine what is important and how changes can be made with the least effect on the character of the building.

As discussed in chapter 2, heritage buildings present low energy performances. Therefore, there is a need of energy efficient retrofitting features and refurbishment strategies. In the last decades of the twentieth century, reducing energy use consisted of simple measures such as shutting off the lights, turning down heating temperature, turning up air-conditioning temperatures and reducing hot water temperatures. Nowadays some of the energy inefficiencies of buildings (related to lighting or plug loads) can be overcome with simple and low cost actions during the life cycle of a building (Santoli et al., 2013). However there are other inefficiencies that require more intricate and thorough retrofitting and refurbishing processes among the elements of a building.

3.1 Retrofitting and refurbishing heritage buildings

The terms retrofit and refurbishment are often used as if they are interchangeable. However, they have different meanings. Retrofit means to provide something with a component or accessory not fitted during manufacture or to add something that did not have when first constructed (Eames et al., 2014). It is frequently related to the installation of new systems (heating systems) but it may also refer to the fabric of a building such as retrofitting insulation, walls or windows. On the other hand, refurbish refers to renovate and redecorate something (especially a building). This process implies improvement by cleaning, decorating and re-equipping. It may include elements of retrofitting. An example of retrofitting is the work carried out in public schools in Rome of the beginning of the 20th century with interventions on external walls and on roofs adding internal cladding (Santoli et al., 2013). An example of refurbishment

is the Bethanie Chapel adapted to an Academy for performing arts in Hong Kong (Yung & Chan, 2012).

Retrofitting and refurbishing heritage buildings aim at achieving enhanced energy performances while maintaining satisfactory service levels and acceptable indoor thermal comfort suitable for contemporary lifestyles using less energy compared to the energy use values before intervention (Moran et al., 2013; Ma et al., 2012). A historic building should be refurbished and/or retrofitted if considered into one of the following categories (Aikivuori, 2006):

- 1) failure in the building due to deterioration;
- 2) change in use;
- 3) optimization of economic factors by improving energy efficiency;
- 4) subjective features of the decision maker;
- 5) change of circumstances.

Figure 4 shows a five phase model developed for refurbishment of public buildings (Mickaitytė et al., 2008). However, the five steps can be considered applicable to any building undergoing a refurbishment and/or retrofitting process. In case of this research, each of the five steps of the model was reinterpreted focusing on heritage buildings. To refurbish a building the first step is an in-depth monitoring in order to improve its energy efficiency. In other words, as a first step, an energy audit should be executed to obtain an energy profile. It is important to create a multidisciplinary team that, through their knowledge, become more aware of energy efficiency problems, exploitation and comfort issues. The team should be comprised by experts in different fields (architecture, engineering, policy, etc.) able to understand the need and requirements of the retrofitting and refurbishing processes. The second phase consists in searching for solutions resorting to tools and techniques available in the market that have been applied in other heritage buildings. In the third phase the obtained solutions need to be evaluated and, mainly, compared between each other so the responsible entities select the most appropriate ones and elaborate a plan. Only then the approval comes of such plan and the required funds from financial institutions. In phase 4, the refurbishment and/or retrofitting of the building takes place. In phase 5, the consequences from the process are analysed. When the need for refurbishment and/or retrofitting is recognized again, the process moves back to phase 1.

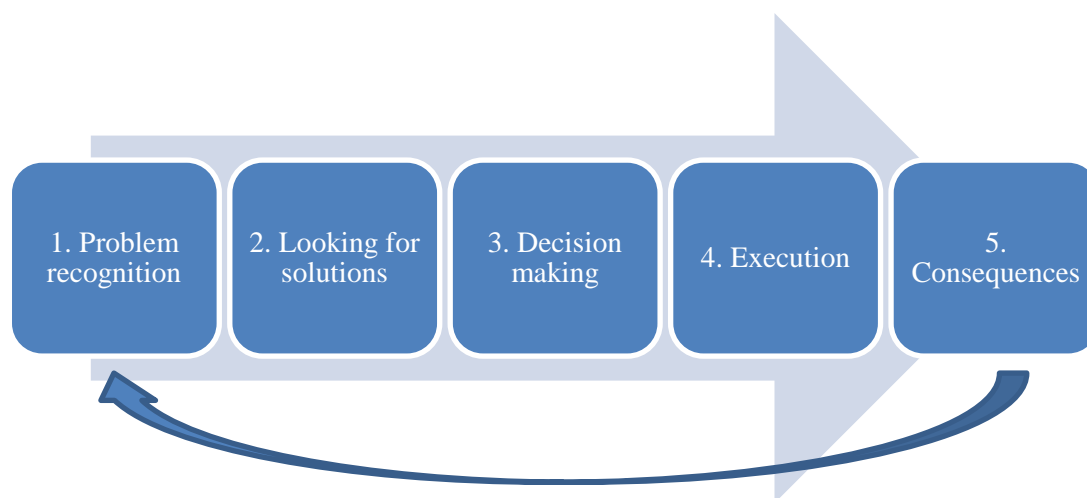


Figure 4 - Five phase model (source: Mickaitytė et al., 2008)

The first phase of the model is problem recognition which is finding the sources of energy inefficiency of heritage buildings. Therefore, next section (Energy audit) goes through the definition and steps within an energy audit. Sections 3.3 and 3.4 present the techniques and tools to evaluate energy performance of heritage buildings. Section 3.6 describes the available retrofitting and refurbishment technologies and processes implemented in heritage building.

3.2 Energy audit

Energy audits are one of the most useful tools for increasing energy efficiency in European countries (Butala & Novak, 1998). An energy audit is defined as a “systematic inspection and analysis of energy use and energy consumption of a site, building, system or organisation with the objective of identifying energy flows and the potential for energy efficiency improvements and reporting them” (EN 16247-1, 2012). Energy audits are key to develop an energy management plan. They aim at determining: i) where the energy goes; ii) how it is used and iii) variances between inputs and uses. Figure 5 shows the steps of an energy audit. The first step consists in collecting all available data about energy systems and energy use pattern of buildings. This data is gathered from the architectural/ mechanical/ electrical drawings and utility bills. Besides the site data it is also necessary to know the annual utility consumption (amount, cost and source). The second step is usually a field survey with the assistance of a building operator with the purpose of finding useful information and engineering data of the building. This phase might elucidate about previous refurbishment and/or retrofitting interventions in the buildings, characteristics of the building envelope, measurement of luminance levels, heating and cooling systems and plug loads. During the third step an evaluation of the possible energy savings is made based on the energy use pattern of the building. It aims at adjusting the energy needed and the energy actually used in order to improve the energy performance of the building. At the end of an energy audit, this information can then be used to improve efficiency, identify energy saving opportunities, reduce operating costs and reduce greenhouse gas emissions (CIPEC, 2011; Krarti, 2000).

In a nutshell, the importance of an energy audit lies in the possibility to identify the sources of over consumption and where it is possible to implement energy saving measures. However, it is crucial that during the auditing, the heritage value and uniqueness of the building is preserved. In other words, when visiting the building all the elements within the building must be kept intact (windows, frames, paintings, etc.) and the recommendations of energy conservation opportunities should always be on behalf of the preservation of the historical value.

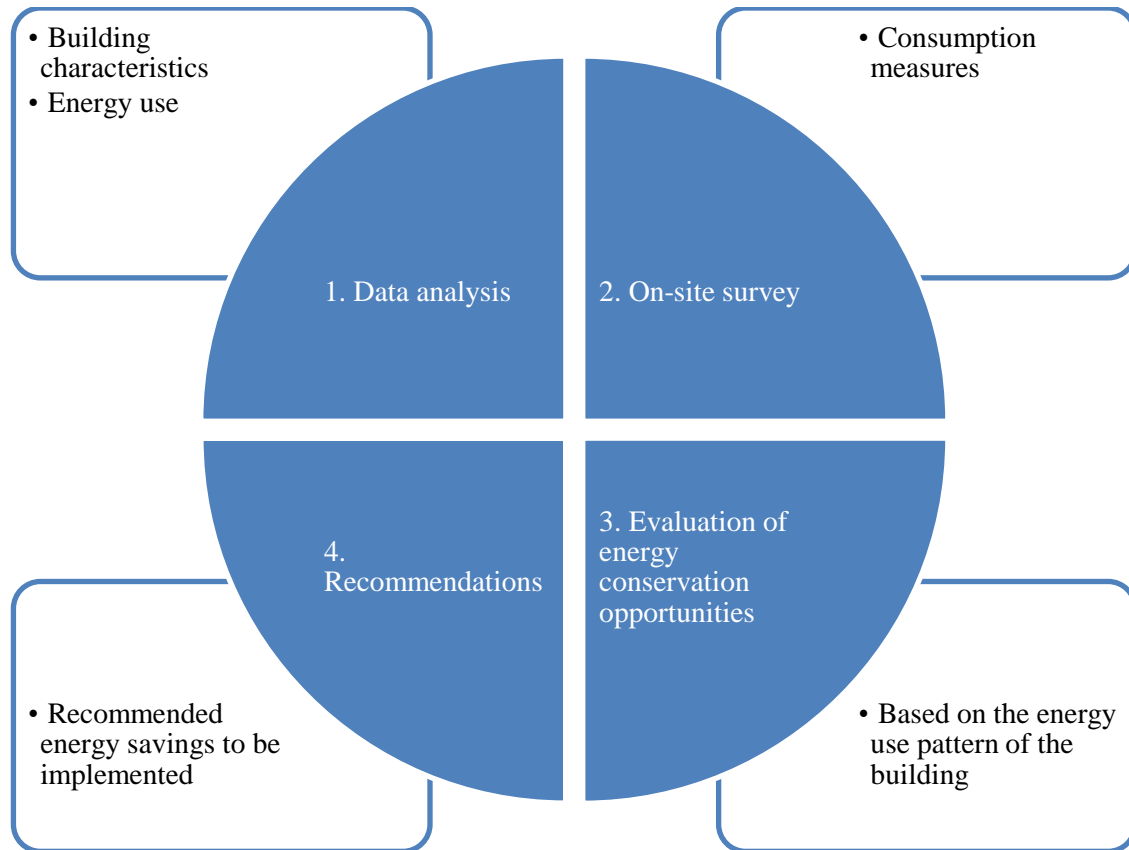


Figure 5 - Scheme of the steps of an energy auditing (source: based on Krarti, 2000)

3.2.1 An energy audit for heritage buildings

For a particular project, the appropriate energy audit can be selected by taking into account the amount of details and level of accuracy required, budget available, project targets, goals defined, and scope of work covered (Ma et al., 2012). In the case of heritage buildings, due to their different characteristics (see 2.1), it is necessary to propose an energy audit which takes into greater account defining aspects such as material and construction techniques, architectural design, historical and artistic importance.

There are some aspects that require a different and careful approach when energy auditing a heritage building. An energy audit is a subjective concept and each and every approach will be different from one building to another. The idea of adopting Mickaitytė et al. (2008) model and the steps of an energy audit from Krarti (2000) is to establish the starting point of an energy audit for heritage buildings. Since it is known that an energy audit is integrated in Mick model (phase 1), the four steps proposed by Krarti (2000) can still apply in heritage buildings. However, each of the steps need to be strictly defined where to focus on. These buildings present some constraints that forbid alterations according to law and to its status. For instance, in step 3 of an energy audit, not all the energy saving opportunities in the market are suitable for heritage buildings. Therefore, according to Butala & Novak (1998), there are three key topics where energy savings can be implemented in heritage buildings. These are building envelope; electrical appliances and heating systems and organisational measures and are explained as it follows:

- The first key topic is building envelope. Building envelope is defined as the parts of a building that form the primary thermal barrier between interior and exterior, also known as the building shell, fabric or enclosure. The energy performance of building envelope components including external walls, floors, roofs, windows and doors, is critical in determining levels of comfort, natural lighting and ventilations, and how much energy is required to heat and cool a building (IEA, 2013). When the building envelope is not sufficiently thermal insulated it can have an important impact on the energy used to condition the building. Improving the building envelope leads to an increase in energy efficiency, occupant comfort and consequently their quality of life.
- Electrical appliances and heating systems refer to what consumes energy inside the building. Energy saving lighting and low consumption electrical appliances will improve energy efficiency of a building. Heating systems without or with deficient automatic regulation and not zoned are a cause for high energy consumption levels. Additionally, boilers that are old, systems that are often unbalanced and heaters without thermostatic valves promote low energy efficiency. The dilemma is whether to reconstruct the heating and the ventilation system separately or to install an energy efficient air heating system with the necessary volume of ventilation air. Therefore, more efficient appliances and heating systems will reflect improvements at energy performance level and also a better indoor air quality.
- The third key topic refers to organisational measures. This concept deals with behaviour/political changes. It also refers to energy use management and maintenance of heritage buildings. Improving energy efficiency and reducing carbon emissions from buildings is not only about heating and insulation of the building fabric. Changing behaviour, avoiding waste, using energy efficient controls and equipment and managing the building to its optimum performance can also improve energy performance of heritage buildings (English Heritage, 2012).

It is certain that heritage buildings are different. These differences manifest themselves more sharply in the three key topics mentioned. The material of construction and architecture are of other times; the equipment consuming energy inside the buildings can sometimes be outdated or inappropriate; and precautionary and conservation measures on these buildings are also of dissimilar calibre. Therefore, it is on those key topics that an energy audit must be subdivided. An energy audit for heritage buildings should be designed by a multidisciplinary team that aware the responsible entities of the heritage buildings of the need to improve their energy efficiency. This team should be comprised by architects, historians, archaeologists, civil/energy/environmental engineers, investors, policy makers. The goal of the multidiscipline is the contribution of each element to understand on one hand the value of the heritage building and, on the other hand, the renovation that the building needs to undergo. Besides designing the audit, this team should also conduct the audit or supervise the performance of the auditor.

Energy auditing assumes a simple energy balance within a building: what comes in equals what goes out (CIPEC, 2011). Figure 6 illustrates this mathematical expression. Energy can leave through a certain area, resulting in energy losses for the building (heat loss, exhaustion, ventilation). As a consequence, energy balances can only be prepared for restricted areas with boundaries defined. The envelope of a building is what defines the boundaries.

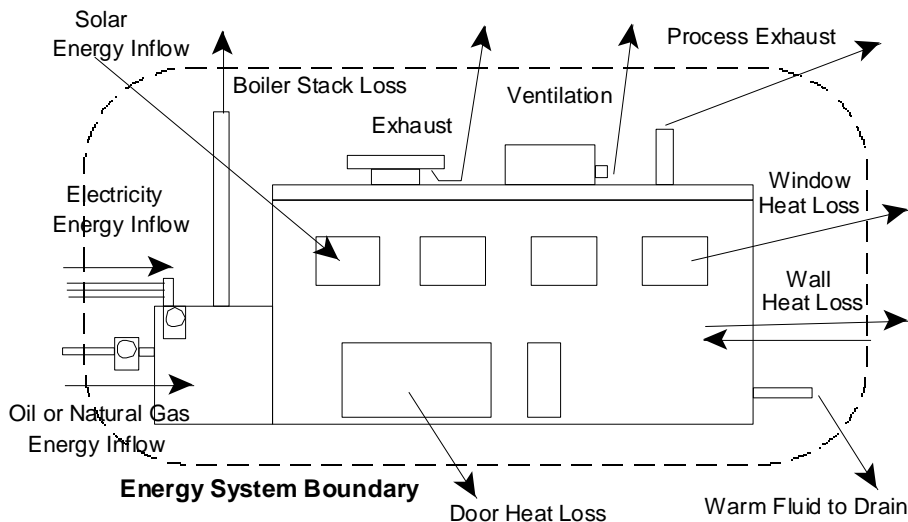


Figure 6 - Energy transfer in a system (source: CIPEC, 2011)

To measure energy flows into and out of a building involves collecting energy flow data from various sources using different tools and techniques. It is possible to estimate energy flows that cannot be directly measured such as heat loss through a wall or vented air. The different techniques to evaluate energy performance of heritage buildings are analysed in the following.

3.3 Techniques to evaluate energy performance of heritage buildings

Energy efficiency measures are required to reduce energy demand. As an example, by adding internal cladding on external walls and roofs, the thermal performance of the building envelope is enhanced (Santoli et al., 2013). According to Taylor et al. (2013) in terms of detailed design and execution on site, the insulation layer needs to be continuous to avoid thermal bridges and the airtightness layer needs to be continuous to reduce infiltration (uncontrolled air movement through gaps and cracks in the building fabric). Furthermore it is suggested that a combination of testing techniques should be used to both measure and diagnose the energy performance³ of a building. Various testing techniques may be used to investigate building performance. These are used in buildings in general and consequently can also be applied to evaluate the energy performance of heritage buildings. The techniques are as follow:

- Air leakage/tightness test

The amount of air leakage through the building envelope or air permeability can be measured using a fan pressurisation method such as the blower door test (BSI, 2001). Also smoke generators can be used to identify areas of leakage in the building or portable smoke pencil to identify leakage in specific locations. The maximum allowable infiltration or air permeability of a building is defined in various standards. Performing this technique will provide data relatively to the process of exhaustion and ventilation that Figure 6 shows.

³ Energy performance of a building examines the energy flow through all the elements of the building shell. It analyse the ways energy is expended to maintain desirable conditions inside buildings. (Cairns & Grimsrud, 1987)

- Thermography

Thermography is the technique used to measure contactless temperature of an object or area. This is used to determine the cause of cold and drafts tracking. The 2D thermography images are surface temperatures shown in different colours. Through this technique it is possible to analyse where the heat losses occur. The heat losses normally occur through windows, doors and walls. Applications of thermography include: identifying delamination of external wall finishes; assessing the effectiveness of external wall insulation (Taylor et al., 2013). Additionally there is a 3D thermal modelling that harnesses the advantages of 2D thermal imaging but with a much higher potential for complete models that can be easily compared over temporal separations. However, this technique is expensive and time consuming. It requires specialist equipment in combination with 2D cameras and it is more difficult to process the data. The 3D model can be visualized in real time by the operator so that they can monitor their degree of coverage as the sensors are used to capture data. This technique can identify and measure thermal irregularities such as thermal bridges⁴, insulation leaks, moisture build-up and HVAC faults (Vidas & Moghadam, 2013).

- Heat flux measurement

Heat transfer is measured by heat flux sensors. Monitoring the heat flows for an extended period of time (typically between 7 and 14 days) makes it possible to derive an *in situ* “U” value for the building element (Doran, 2000).

- Co-heating test

This technique is described as for the thermal calibration of houses (Taylor et al., 2013). It aims to measure heat losses resulting from both infiltration and thermal transmission through the building fabric. “Co-heating” refers to the energy balance for the building during the test: under steady state conditions, the transmission and ventilation heat losses are balanced by heat gains from both electrical and solar heating. The heat loss co-efficient can then be calculated for the building by plotting the daily heat input against the daily average difference in temperature between the inside and outside of the building.

3.4 Tools to evaluate the energy performance of heritage buildings

This section presents the tools used to evaluate the energy performance of buildings. These tools are used – in buildings in general – to perform the tests discussed in section 3.3.

- **Blower door to perform air leakage/tightness test**

Blower Doors is a tool used to measure the tightness of the air which is the major building factor in determining infiltration and air leakage. These can lead to heat loss, unpleasant drafts, and problems with moisture, mildew and ice dams. By quantifying the air loss, it is possible to determine the potential savings by actions like home weatherization and air sealing. Blower doors are capable of pressurizing and depressurizing a building and measuring the resultant

⁴ Thermal bridges are discontinuities in thermal barriers and occur when there is a gap between materials and structural surfaces (Totten et al., 2008).

airflow and pressure. This technology can be used in a variety of ways with different purposes such as energy, air quality, comfort and safety. A blower door test locates air infiltration by exaggerating the defects in the building shell (US Department of Energy, 2012). However, this type of test only measures air infiltration at the time of the test. Changes in atmospheric pressure, weather, wind velocity, or any activities of the occupants that may affect air infiltration are unaccounted.

Blower doors are still used to find and fix the leaks but the values generated by the measurements are more often used to estimate infiltration for both indoor air quality and energy consumption estimations. These estimations are used for comparison to standards or to provide program or policy decisions (Kreith & West, 1997). The construction quality of the building envelope plays an important part having to assure that the envelope is tight enough so leakage does not affect energy, comfort or airflow. Hence, the construction quality of the building envelope plays an important part having to assure that the envelope is tight enough so leakage does not affect energy, comfort or airflow. Blower Door data estimates airflows at a variety of pressures and mostly at a 50 Pa pressure difference (Sfakianaki et al., 2007). In case of buildings with many leaks and particularly large buildings, the airtightness measurement should be performed at 25 Pa instead of 50 Pa (Pfluger & Baldracchi, 2011). The advantage of this method is that their results are less affected by climatic conditions. During the measurements a fan is used to supply or exhaust air from dwellings at rates required to maintain a specified pressure difference across the building envelope, as shown in Figure 7.



Figure 7 - Set-up equipment of a blower door for the measurement of air tightness (source: Chen et al., 2012)

The air flow and the pressure difference are measured once and again; after the test conditions are stabilized, the measurements are recorded (Chen et al., 2012).

- **Infrared camera to perform thermography**

An infrared (IR) camera is used to assess temperature distribution in the interior or exterior surfaces of a building envelope. It can detect uninsulated wall sections, air leaks and moisture. This technique is referred to as thermal imaging or thermography. Localised reductions in the thermal conductivity of the building envelope (caused by flaws in the insulation layer or thermal bridges) will result in surface temperature variations if a stable difference of temperature is established between the inside and outside of a building (Taylor et al., 2013). Under suitable environmental conditions, these surface temperature variations can be detected using an IR camera. Wind pressures can also provide a driving force for infiltration through cracks or gaps in the building structure. Therefore, inspecting areas of the building that are exposed to strong winds with an IR camera enable identification of air leakage. Although dependent on the weather, this approach dispenses mechanical fans (Siddall, 2009).

In addition to identifying insulation defects and thermal bridges, thermography is also used to locate air leakage paths in the building envelope. Air leakage can be observed internally when the building is depressurised (e.g. during an air leakage test) provided there is a difference between internal and external air temperatures. Figure 8 shows the appearance of some typical insulation and air leakage defects.

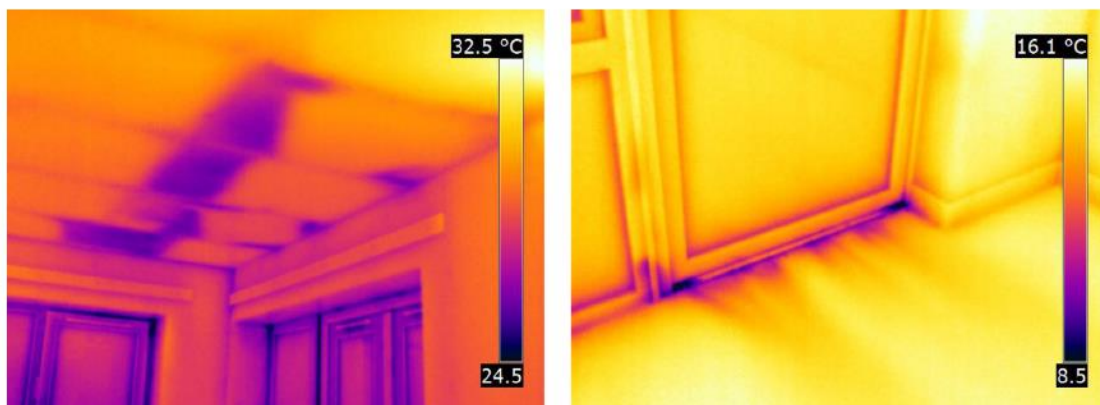


Figure 8 – Construction flaws identified using thermography: on the left) an area of ceiling where insulation above was installed incorrectly; on the right) air leakage below a door cools the surface of the surrounding floor. (source: Taylor et al., 2013)

Modern infrared cameras have simplicity of operation and decreasing costs that means the technology is more accessible to non-specialists even if the correct interpretation of results requires a working knowledge of the building and the underlying physics involved. Without contradicting the benefits of formal training in thermography, some problems are relatively easy to locate with an IR camera (e.g. insulation defects).

- **Heat flux sensors to perform heat flux measurement**

Heat exchange is measured with heat flux transducers. Heat flux transducers are used to determine thermal properties of buildings and materials. This tool contains two thermopiles separated by a matrix with a fixed thermal resistance. When heat flows through a heat flux transducer the matrix causes a temperature gradient to develop between the two thermopiles. By

the Seebeck effect⁵, each thermopile generates a voltage proportional to its absolute temperature. The differential voltage between the two thermopiles is proportional to the temperature gradient and therefore, since the thermal resistance of the matrix is fixed, to the heat flow through the heat flux transducer (Perl et al., 2004). With heat flux transducers it is possible to measure heat gain or heat loss by radiation, convection and conduction. The evaporative heat loss cannot be measured with heat flux transducers, because the water vapour is not able to pass through the heat flux transducer.

- **Temperature sensors to perform heat flux measurement**

Thermocouples are the most commonly used temperature sensors because they are relatively economical yet accurate sensors that can operate over a wide range of temperatures. Their functioning is also based on the Seebeck effect. A thermocouple consists of two wire legs made from different metals. The wire legs are welded together at one end, creating a junction where the temperature is measured. When the junction experiences a change in temperature, a voltage is created (National Instruments, 2012). The voltage can then be interpreted using thermocouple reference tables to calculate the temperature.

- **Electrical heaters and thermostatic controller to perform co-heating test**

The co-heating test involves heating the inside of the building with electrical heaters controlled by a thermostat to achieve a static internal temperature of approximately 25°C (Johnston et al., 2012). During months that typically require heating (i.e. when the inside of the building reaches approximately 25°C) the internal air starts to cool and the electrical heaters start working again. Since the energy that goes in equals the energy that goes out of a system and knowing the efficiency of the electrical heaters, the energy consumed is acknowledged. Consequently, the losses can be calculated.

- **Temperature and relative humidity sensors to perform co-heating test**

There is a great variety of temperature and relative humidity sensors in the market. What is expected from these kinds of sensors is an accurate relative humidity sensing, with fast response time and durability. The sensor outputs a precise temperature and relative humidity measurement to the HVAC control module to optimize the efficiency of a building.

- **kWh meter to perform co-heating test**

An energy meter is the device that measures the amount of electrical energy supplied to or produced by a residence, business or machine. The device records other variables including the time when the electricity was used. Modern electricity meters operate by continuously measuring the instantaneous voltage and current and finding the product of these to give instantaneous electrical power (watts) which is then integrated against time to give energy used (joules, kilowatt-hours, etc). The most common type is a kilowatt hour (kWh) meter. When to evaluate energy performance of a building, the co-heating test requires the daily heat input to

⁵ Seebeck effect was discovered in 1821 by the physicist Thomas Seebeck. The effect consists of the conversion of temperature differences into voltage (Pollock, 1985).

maintain the internal temperature and it is determined from measuring electrical energy consumed by a kWh meter.

3.5 Summary of energy performance evaluations of heritage buildings

3.5.1 Layout of an energy audit to be performed in heritage buildings

An energy audit is a subjective process depending on the building under study. However, there are common steps to energy auditing in any type of building. These are: 1) data analysis; 2) on-site survey; 3) evaluation of energy conservation opportunities; and 4) recommendations. Historic buildings have different characteristics such as their ability to breath and their high thermal mass. These characteristics are due to the architecture and fabric design applied at the time of their construction. Therefore, an energy audit for heritage buildings should focus in the following three topics: i) building envelope, ii) electrical appliances and heating systems and iii) organisational measures. When carrying out an energy evaluation of a heritage building, it makes sense to divide this evaluation among what is structural – building envelope –, what consumes energy – electrical appliances and heating systems – and what depends on the responsible entities and users – organisational measures. The building envelope has strict rules about what can be altered. As an example, in Hungary, external insulation is unauthorized in buildings listed as heritage by the National Office for Cultural Heritage (Alexa et al., 2014). This is the particularity and challenge of working with heritage buildings: energy performance must be improved and, at the same time, the inheritance and culture must be preserved.

Since there is no legislation regarding energy performance in heritage buildings, it is up to a more conscious multidisciplinary generation to do something on that behalf. Proposing a layout of an energy audit specific to heritage building may be a starting point.

Figure 9 presents the layout proposed to perform an energy audit in a heritage building.

	Building Envelope	Electrical appliances and heating systems	Organisational measures
1) Data Analysis			
2) On-site survey			
3) Evaluation of energy conservation opportunities			
4) Recommendations			

Figure 9 - Lay-out of an energy audit for heritage buildings

It has four steps and each step should audit the building envelope, the equipment consuming energy and use and maintenance policies of the space. That is to say that in the first phase

energy bills should be analysed along with the occupation/function of the building and building structure, but also an inventory of electrical appliances and heating systems. The topic of organisational measures may not be applicable depending on the case as buildings may not present any conservation plan at the time of the audit. At the end of phase 1, the first line of the table will be filled in and the auditor will be ready to schedule an on-site survey. The major advantage of phase 2 is the personal contact with someone responsible for the building and an *in situ* examination. The fact of being on site allows the auditor to witness the status of the building looking at every element of the building envelope and energy systems. In phase 3, the aim of this layout is to clearly divide where to look for energy conservation opportunities through techniques that evaluate the energy performance. Therefore, opportunities will be found to improve the energy efficiency through building envelope, electrical appliances and heating systems and organisational measures. Once this line of the table is complete, the auditor already knows which recommendations to put forward. Figure 10 explains each part in which an energy audit should be divided.

The energy audit should be divided in 3 parts. The content of each of the three key topics to improve energy performance in heritage buildings are as follows:

Building envelope

- Windows
- Draught-proofing
- Floors
- Walls
- Roofs
- Shading devices

Electric appliances and heating systems

- Electric appliances
- Heating systems
- Boiler
- Lighting
- Passive heating and cooling
- RES integration

Organisational measures

- Condition and quality of the building
- Maintenance
- Repair works

Figure 10 - Description of the three key topics to improve energy performance

These three topics/parts are of much importance guaranteeing the heritage status to the building. Again, the benefit of using this layout is to detach all the elements to analyse, narrowing down the solutions that will lead to an improved energy performance.

3.5.2 Diagnostic and monitoring tools to evaluate energy performance of heritage buildings

Diagnostic and monitoring tools to evaluate energy performance in buildings were described in sections 3.3 and 3.4. These techniques and tools can be suitable in any kind of building. Air leakage test helps finding the source of draughts and infrared thermography enables to see where energy is leaking out of the building. Other testing and analysis includes heat flux measurement which compares the in-situ “U” value results to the “U” values calculated from published data and co-heating test which measures the energy efficiency of a building. Table 2 shows a summary on these techniques and tools, giving also a description of each one.

It is commonly found in literature that one technique often performed to evaluate energy performance in heritage buildings is a thermography. This might be because the only tool needed is an IR camera while other techniques require more than one tool to be performed. Given the specific needs of heritage buildings such as to diminish energy use values and improving comfort; performing a thermography comes as the most suitable technique. A thermography can be performed without moving objects or changing the building conditions. Additionally, through a thermography it is also possible to determine the air tightness of a building. In contrast, other techniques only focus on one aspect. Hence others techniques additionally have other demands such as unoccupied areas and minimal access during the tests in order to maintain steady conditions.

Table 2 - Summary table on the techniques and tools to evaluate energy performance

Technique	Description	Tool	PROs	CONs	Reference
Air tightness	Air permeability and location of air leakage paths	Blower door	When done in conjunction with a thermography t it can provide accurate information on the presence and location of air infiltrations and thermal bridges.	Depending on the flow rate, it may require more than one blower door.	(Pfluger & Baldracchi, 2011; Pfluger et al., 2013)
Thermography	Assessment of insulation continuity and measurement of thermal irregularities	IR camera	Measures the losses of energy through the façades and distribution system.	The results of a thermography should be analysed in conjunction with accurate evaluation of thermal parameters, building materials and effects of the boundary conditions.	(Spodek & Rosina, 2014)
Heat flux	Derivation of an <i>in situ</i> “U” value for the building element	Heat flux sensors Temperature sensors	The calculated values do not account for the effect of mortar, voids, etc., which are included in the <i>in situ</i> measurements.	<i>In situ</i> “U” values are lower than expected (from standard values of the thermal conductivity of stone).	(Baker, 2008)
Co-heating	Heat losses measurement resulting from both infiltration and thermal transmission through the building fabric	Electrical heaters and thermostatic controller Temperature and relative humidity sensors kWh meter	Elimination of human behaviour variables.	Restricted access during the test and usually carried out during winter months.	(Wingfield et al., 2010)

The technique that seems to be the best choice to evaluate energy performance in heritage buildings is a thermography. Once the energy audit is done and analysed, the next step is to look for solutions. The refurbishment and retrofitting techniques available in the market for heritage buildings are presented in the next section.

3.6 Refurbishment and retrofitting techniques

After performing an energy audit in a heritage building, it is possible to draw an energy profile of the building under study and reflect on where to make changes to enhance energy performance. This next section presents the existing solutions available today to diminish their energy consumptions levels of heritage buildings. These solutions are presented according to the lay-out for energy audit given in 3.5.1.

3.6.1 Building envelope

- **Windows**

The design of the windows is a significant factor in shaping the overall character of the building. There are two main considerations regarding window appearance: the frame and the glazing. Some manufactures can fit double glazed panes into existing timber window frames, to obey to older framing styles. Being a heritage building restricts the replacement options and there are local authorities that do not permit double glazing. Consequently secondary glazing is often considered to have less of an impact to the appearance of the window than double or triple glazing. Secondary glazing consists of a second window installed internally next to the original window reducing both radiated heat loss and air leakage (Change Works, 2008). This option is generally acceptable from a building conservation perspective if the retrofitting is not damaging the building but brings some disadvantages with it. Intrusion into the room, loss of usable window ledge space, loss of use of internal shutters, the need to reposition curtains and blinds and a double reflection visible from outside are some of the disadvantages (Change Works, 2008). However, separating the thermal insulation layer from the external glazing of the window seems to be the best solution that will help maintain the external original appearance while the internal insulation layer enhance comfort, hygiene and air tightness.

A “smartwin historic” is a solution suggested by Rambelli et al. (2013) that gives the possibility to both keep the historical habitus of the window and achieving comfort of a modern window. This window system is based on a compound window basis, a box window basis and both with two layers. The outer layer is the part respecting the requirements for the historical aspect. The inner layer is the main energy efficient element with triple glazing, insulation, gaskets and fittings able to support the weight of the glazing.

- **Draught-proofing**

According to Change Works (2008), sealing draughty gaps in a heritage building, is unlikely to cause problems associated with over-sealing, as the historic building materials are porous. If

sealing redundant flues, careful is needed to prevent moisture becoming trapped in the space and causing deterioration. At floor level the easiest way of sealing gaps is by using a gunned mastic material in gaps between the floorboards or skirting. For draught-proofing doors and windows, the same principles apply: heavy-duty materials are particularly advisable for doors due to wear and tear from frequent opening and closing the doors. As a rule of thumb, historic buildings need to be ventilated at a rate of 0.8 to 1.0 air changes per hour – a modern building requires two times that value. Since infiltration rates in many historic buildings exceed this value, draught-proofing is beneficial (English Heritage, 2008).

- Floors

It is possible to install insulation to reduce the heat loss from floors whether there are solid floors built directly on the surface of the ground or suspended timber floors (floorboards laid across timber joists). There are two ways to install floor insulation: from below or from above. The choice of insulation type and method will depend on the original floor type. Suspended timber floors in historic buildings commonly have a layer of deafening material below the floorboards, laid between the joists. This can be an effective fire retardant and so should not be removed. However, it is possible to make space more limited so thinner solid insulation panels or insulating foam may be more appropriate than insulating quilt (Change Works, 2008).

According to Change Works (2008) the installation of insulation in heritage buildings from below suspended timber floors is relatively simple as long as there is sufficient space to access this area (900mm crawl space is the minimum recommended). Insulation is then fitted between the joists and held in place with netting. A variety of insulation materials can be used in this situation. Ideally these should be vapour permeable such as wood-fibre, compressed hemp, wool of sheep (English Heritage, 2012c). Installation of insulation from above suspended floors is the situation most frequently found in historic buildings, particularly where the boards can be lifted without unacceptable levels of damage (English Heritage, 2012c). If boards are to be lifted for any other reason it would normally be appropriate to take the opportunity to install insulation at the same time. Once the floorboards have been removed, the installation process is the same as described to insulation from below. However, the mesh netting is fixed in place between the joists before the insulation is laid. Afterwards, the floorboards are re-laid. Suitable materials are semi-rigid batts, boards or loose fill cellulose (English Heritage, 2012c). When insulating solid floors in heritage buildings the most common method is to install a floating floor with integral insulation. In historic buildings this can be an issue due to the fact of covering the historical floor – it is unlikely to be accepted. Retrofit options for ground floor rooms with solid floors include replacing carpets with wooden floors or tiles to expose the cooling effect of the ground (Roberts, 2008).

- Walls

Historic paintings and frescos present on the walls and ceilings are the reason why in historic buildings interventions and additions in walls and ceiling structures are doubtful, (Pfluger and Baldracchi, 2011; European Renewable Energy Council, 2009). Solid walled buildings, particularly those with thicker walls have comparatively high thermal capacities, which means they can absorb heat over time and release it relatively slowly as the surroundings cool down (Aste et al., 2009). External insulation means little of this heat will be lost to the exterior. This allows a building to maintain a level of warmth over day-night heating and cooling cycles,

improving human comfort and potentially reducing overall energy use (English Heritage, 2012a).

English Heritage (2012a) states that external insulation systems comprise insulation layer fixed to the existing wall and a protective render or covering installed on top to protect the insulation from weather and mechanical damage. However, this type of insulation requires adaptation to the roof and wall junctions, around window and door openings and the repositioning of rainwater down-pipes what can modify the appearance of a building. External insulation should normally be considered as a two-component system. Useful materials for the external insulation itself include hemp-lime composites, wool of sheep and mineral wool (English Heritage, 2012a). Moisture-permeable finishes to protect the insulation materials from weather and mechanical damage include: lime renders and rain-screen cladding (English Heritage, 2012a). Cellulose fibre is too susceptible to damp to be used externally. Internal insulation is usually applied directly to the inner face of the external wall and then a finish is installed to the room side. A non-rigid insulating material will often be installed between timber studs or battens erected internally to the wall, with the new internal finish applied to the timber structure (English Heritage, 2012a). Occasionally there may be a cavity between the insulating layer and the original wall. An example of this is the kind of insulation retrofitting performed by Harold Janssen in the Netherlands which outside walls were untouchable and the solution a secondary glass wall inside at a distance of 1 meter (Janssen, 2013). In listed buildings, consent will be required for any internal alterations that affect the appearance and character, including any materials, details and finishes of historic or architectural interest. In many cases this may simply make the installation of insulation unacceptable. Almost any insulation material available can be used internally, subject to proper control of vapour and careful isolation from sources of dampness (English Heritage, 2010). The conceivable internal finishes can be applied either to replicate the original or to introduce a new design.

Vacuum insulation panels (VIPs) are a novel thermal insulation component used in refrigerators and cold shipping containers which during the last decade, also have been introduced in the building industry (Johansson, 2012). Johansson (2012) describes this solution as a micro-porous core structure enclosed in a thin gas-tight envelope, to which a vacuum is applied. Furthermore the author affirms that VIPs have a thermal performance five to ten times better than conventional insulation and it can be placed on the interior or exterior of the existing structure. However, it is recognised that VIPs are fragile compared with conventional construction materials and edge effects are significant, requiring careful design and fabrication. Another technology is multi-foil insulation, which is made up of multi-layered reflective films only a few micrometres thick. These layers, which are separated by wadding such as foam or wool of sheep, are sewn together to form a thin insulating blanket. The total thickness of a multi-foil is about 30 mm (Roberts, 2008). In summer multi-foil insulation reflect radiant heat; in winter it retains the heat and prevents cold air from penetrating the building (ACTIS, 2010). In case of inside wall insulation, Pfluger and Baldracchi (2011) suggest capillary active thermal insulation materials or vapour retarder dependent on the relative humidity in combination with airtight construction of embedded wooden beam ends.

- Roofs

As warm rises the roof is an important place to insulate and it is also one of the easiest places to add insulation in most buildings (English Heritage, 2012). Regardless of the location, insulation should be installed avoiding potential fabric and structural damage (timber rot due to

condensation on the roof timbers) or cold bridging and condensation within the home (i.e. the habitable rooms below roof). It is possible to install insulation to reduce the heat losses whether the roofs are pitched or flat (European Renewable Energy Council, 2009).

In a traditional pitched roof, insulation is installed directly from above the top floor ceiling between the ceiling joists. The main conservation considerations surrounding insulation of roofs relate to ventilation and moisture control. The warm air rising to the roof space carries moisture which will condense on the underside of the roof and the timbers causing rot. Insulating the loft reduces this flow of warm air, but moisture will still enter. So it is important that the roof space is well ventilated to allow any moisture to disperse. Loft insulation can be made from a variety of materials, ranging from mineral fibre to natural materials such as wool of sheep (Change Works, 2008). Flat roofs typically have a structure with waterproof covering laid over timber decking on timber joists (English Heritage, 2012e). The majority of insulation materials appropriate for use in historic buildings are vapour permeable. The lowest densities and highest insulation values are gained from soft fibre rolls or unformed loose fill materials (English Heritage 2012e). These materials are incapable to support their own weight or of any other materials and should be placed loose with nothing covering them.

Green roofs are an innovative solution that can reduce the amount of heat penetration through roofs and in this regard play a similar role to roof insulation. They reduce the roof temperature by absorbing heat into their thermal mass and because of evaporation of moisture (Castleton et al., 2010). Two examples can be given to show incompatibleness and compatibleness of green roofing in historic buildings. The first one in Figure 11 showed to be incompatible because the green roof features were visible along the street where the building stands. Although the buildings have substantial parapets, the trees which can be seen from the street below, negatively impact the character of these late nineteenth century historic buildings. Figure 12 shows the second example which consists of planted terraces used by tenants of the penthouse offices that were also added as part of the rehabilitation of an early twentieth century building. The green roof increases the energy efficiency of the building and the green groundcover also acts as an acoustical damper for the rooftop offices. The tall parapets hide the green roof ensuring that the historical character of the building is retained while incorporating this energy efficient and environmentally-friendly feature (Petrella, 2009).



Figure 11 - Incompatible solution: the plantings were highly visible above the parapet wall (source: Petrella, 2009).



Figure 12 - Compatible solution: the tall parapet wall prevents the viewing of the green roof sections from the street below (source: Petrella, 2009).

- Integration of shading systems within window/ glazing system

Shading devices can be either fixed or movable. Since windows are most often untouchable on historic buildings and the only source of daylighting the possible positions for the integration of shading systems are limited.

According to Pfluger & Baldracchi (2011) in southern regions the single glass type window is very typical for historic buildings, whereas in northern regions casement windows are usual. In case of single pane windows only internal shading systems seem to be suitable. For casement type windows the spaces between the glasses could be used for shading system integrations.

3.6.2 Best practices on building envelope refurbishment of heritage buildings

For historic buildings an appropriate balance needs to be achieved between building conservation and measures to improve energy efficiency if lasting damage is to be avoided both to the character and significance of the building and its fabric (English Heritage, 2013a). For example, Roberts (2008) states that it would be neither sustainable nor cost effective to replace a 200-year-old window in a heritage building that is capable of repair and upgrading with a new doubled-glazed alternative, and even less so if the new window were to have an anticipated life of only 20-30 years. Insulation to roof and external walls are the most effective building interventions.

Table 3 presents a summary of the techniques that offer the least possible damage to architectural design regarding the different elements within the building envelope (i.e. windows, draught-proofing, floors, walls and roofs). It also shows the solutions that have been applied to heritage buildings and an innovative solution if that is applicable. An innovative solution is something that has recently been developed and is not yet much in use. They are solutions that prospect greater effectiveness in reducing energy consumption when compared to the solutions mostly adapted to heritage buildings. This table presents the best practices available in order to refurbish and/or retrofit a heritage building. However, when buildings have a list of constraints not allowing changes in the building envelope or the use of certain equipment, the

refurbishment approach may ask for different solutions. If that happens to be the case, a multidisciplinary team must prepare an innovative approach to address each specific case. In the same way as with the energy audit, overcoming these constraints will require the creation of a multidisciplinary team consisting of architects, historians, civil engineers, civil society, policy makers, etc.

Table 3 - Summary table for the best techniques regarding the building envelope

Element	Type	Most adopted solutions	Innovative solution	Additional information
Windows		Secondary glazing - a second window installed internally next to the original window reducing both radiated heat loss and air leakage. This option is generally acceptable from a building conservation viewpoint if the retrofitting is not damaging the building (Change Works, 2008).	“Smartwin historic” is based on a compound window basis: a box window basis and both with two layers. The outer layer is the part respecting the requirements for the historical aspect. The inner layer is the main energy efficient element with triple glazing, insulation, gaskets and fittings able to support the weight of the glazing (Rambelli et al., 2013).	The first prototype was installed in the Waaghau in Bolazano, Italy, in February 2012 (Engelhardt, 2012).
Draught proofing		Gunned mastic material in gaps between the floorboards or skirting. For draught-proofing doors and windows, the same principles apply: heavy-duty materials are particularly advisable for doors due to wear and tear from frequent opening and closing the doors (Change Works, 2008).		
Floors	Suspended floors	From below the floor: with wood-fibre, compressed hemp, wool of sheep (English Heritage, 2008c). From above the floor: with semi-rigid batts, boards or loose fill cellulose (English Heritage, 2008c).		
	Solid floors	Replacing carpets with wooden floors or tiles (Roberts, 2008).		The energy saving resulting from insulating solid ground floors can in many cases be very diminished mainly because the ground beneath maintains a stable temperature of around 10°C (English Heritage, 2012d).

Walls	Internal insulation	Internal insulation is usually applied directly to the inner face of the external wall and then a finish is installed to the room side. Non-rigid insulating material will often be installed between timber studs or battens erected internally to the wall, with the new internal finish applied to the timber structure to control vapour and careful isolate from sources of dampness (English Heritage, 2012a).	Vacuum insulation panels consist in micro-porous core structure enclosed in a thin gas-tight envelope, to which a vacuum is applied VIPs have a thermal performance five to ten times better than conventional insulation (Johansson, 2012; Roberts, 2008).	Historic Austrian walls (clay bricks) built during 19 th century with VIP sandwich panels (Buxbaum et al., 2010).
	External insulation	External insulation systems comprise insulation layer fixed to the existing wall and a protective render or covering installed on top to protect the insulation from weather and mechanical damage. Useful materials include hemp-lime composites, wool of sheep and mineral wool (English Heritage, 2012a).	Multi-foil insulation is made up of multi-layered reflective films only a few micrometres thick. These layers, which are separated by wadding such as foam or wool of sheep, are sewn together to form a thin insulating blanket. The total thickness of a multi-foil is about 30 mm (Roberts, 2008).	
Roofs	Pitched	Insulation is installed directly from above the top floor ceiling between the ceiling joists and it is generally referred to as loft insulation. Considering ventilation and moisture control a variety of materials can be used from mineral fibre to natural materials such as wool of sheep (Change Works, 2008).	Green roofs Green roofs can reduce the amount of heat penetration through roofs and in this regard play a similar role to roof insulation. They reduce the roof temperature by absorbing heat into their thermal mass and because of evaporation of moisture (Castleton et al., 2010).	
	Flat	The majority of insulation materials appropriate are vapour permeable. The lowest densities and highest insulation values are gained from soft fibre rolls		

		or unformed loose-fill materials (English Heritage 2012e).	
Shading devices	Single glass type window	In southern regions the single glass type window is very typical (Pfluger & Baldracchi, 2011).	Historic buildings with single glazing, shutters and full length curtains could be as effective as double glazing, when preventing heat from leaving the room (Uspenskiy, 2013)
	Casement type windows	In northern regions casement windows are usual. For this solution spaces between glasses for shading integration (Pfluger & Baldracchi, 2011).	

3.6.3 Electrical appliances and heating systems

- Electrical Appliances

Heritage buildings have today different purposes than the ones from the past. Their adaption into conference rooms, hotels and libraries justify the need of acquiring electrical appliances. Appliances have an energy labelling which is a tool to inform consumers about their energy efficiency. Energy label starts on A, being the one that provides greater savings in energy consumption. Figure 13 shows the new energy label, released in 2012, which added three efficiency classes (A +, A ++ and A +++) and eliminated the "E", "F" and "G" classes to the previous label. For the same capacity and characteristics, a device rated as A +++ is considered more efficient and economic (EDP, 2012). In other words and as an example, opting for refrigerators and freezers rated as A +, A ++ or A +++ provide savings of about 20%, 40% and 60%, respectively, compared to class A.

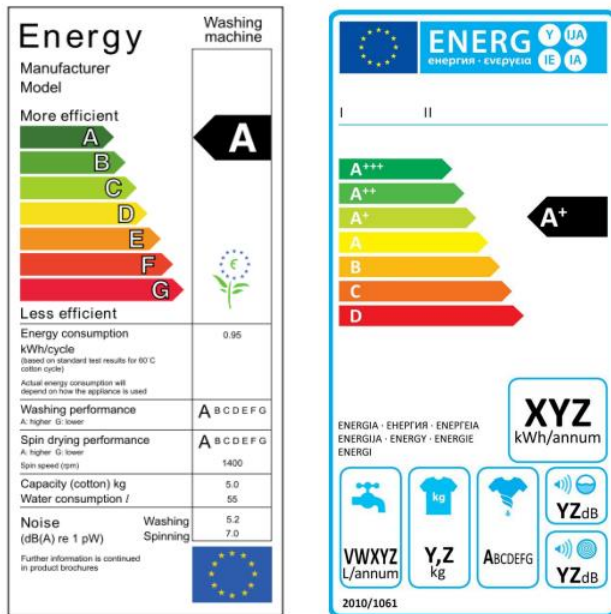


Figure 13 - Old and new energy label [since the recast of the Directive (2010/30/UE)], (source: ADEME, 2013)

The energy labelling system could make that those responsible for heritage buildings become aware of the ways energy and money can be saved. Smart monitors (sometimes called real time display units) show the amount and cost of electricity usage at any time, together with the greenhouse gas emission levels. The readings change as appliances are turned on and off, so the energy consumption of individual appliances can be calculated (Molina-Markham et al., 2010).

- Heating systems

Central heating system is one of the most effective ways of heating and it can be a dry system or a wet system. Dry system comprises storage heaters that retain the heat in internal thermal blocks and release the heat over time at a variable rate. However, with this system it can be difficult to control room temperatures and it requires a separate water heating system (Change Works, 2008). Wet system differs from a dry system on having hot water circulating around via

radiators which radiate the heat from the water into the rooms or through underfloor coils. These systems maximise effectiveness but it is important to retain the appearance and character of the historic property. Although portable heaters and electrical oil-filled are alternative options to central heating systems, they are less efficient and more expensive. Besides application of modern technology, an energy efficient heating system is controlled by time or temperature. It may include: an electronic timer, a room thermostat, and thermostatic radiator valves (Change Works, 2008).

Pfluger & Baldracchi (2011) overviewed possibilities of integration of a heat exchanger in the building structure such as integration in walls and ceilings. In most cases the systems are not really integrated into the structure of the building. Nevertheless, an active overflow prototype (Figure 14) was constructed and tested in a heritage building working as a school. The idea is to vent fresh air into the corridor and staircase with fans actively pushing the air from the corridor into the classrooms. Typically, to optimize this approach the ventilation system is linked to a heat recovery and therefore ducts for air inlet and exhaust to and from the rooms. Silencers are also needed to prevent noise. The prototype aims at avoiding the need for ducts in the corridor or for the installation of a vertical shaft to provide fresh air. The heat recovery system is instead placed on the attic and the fresh air is distributed via the open staircase and corridors through vertical ducts. For protected buildings, this is an advantage compared to decentralised systems with two openings per room (in and outflow) to the outside (impacting on the building structure). Hence this solution should only be applied for heritage buildings (Rambelli et al., 2013).



Figure 14 - Prototype of active overflow system (source: Rambelli et al., 2013)

- Boiler

Modern technology can offer distinct enhancements to the thermal performance of older buildings whatever their construction and age (English Heritage, 2012b). Gas boiler systems are the most common generation system in heritage buildings having efficiency between 80% and 95%. A condensing boiler has similar components of a gas boiler but it also makes use of the heat produced during the operation which otherwise would be lost increasing its efficiency (with heat recovery). For example, condensing boilers are highly efficient and with effective controls and programming can make heating systems work in ways which are relatively harmonious with the construction of heritage buildings (Change works, 2008).

- Lighting

Interventions as additions in the wall and ceiling structures are limited in heritage buildings. Therefore, according to Pfluger & Baldracchi (2011) artificial lighting installation is defined to be a difficult requirement which can be fulfilled by stand-alone-solutions such as floor lamps. It is also recognised that currently there are not many luminaires available on the market aligned for the lighting of historic buildings. In general it can be said that the artificial lighting in historic buildings is much reduced. As solutions, consistent with the needs of conservation of spaces, efficiency and energy savings, LED technology is ideal for buildings in which invasive refurbishment is not an option. The use of LEDs allows the luminaire to reproduce the illumination given by incandescent lighting: 2700K (Weitlaner, 2013). An illumination concept was developed, that is able to fulfil the human and material requirements (Rambelli et al., 2013). Figure 15 shows the luminaire “wallwasher”, which can be installed in a non-invasive way. It provides on one hand optimized visual scenery and on the other hand it should slow down the deterioration process that any material undergoes in its natural (or artificial) environment.



Figure 15 - Prototype of luminaire (source : Rambelli et al., 2013)

- Passive heating and cooling

In order to understand the potential performance of the passive solutions originally conceived during the building design and realisation, Pfluger & Baldracchi (2011) advocates that it is essential to know when the building was built, its original use and its evolution through times in terms of renovations and changes of use. Therefore a whole geometric survey, the identification of the materials and of the heating/cooling strategy and systems are requested. Passive heating of buildings is possible through direct heat gain and/or thermal storage methods, that is, using transparent surfaces to gain heat and wall to storage it, making it available for the night. Direct heat gain method is simple and cheap, but it depends on climatic loads swings (Pfluger & Baldracchi, 2011). Especially in moderate or cool climates, the passive heating solutions should be studied together with the cooling ones in order to avoid overheating and glazing by daylight. Passive cooling is made mainly by increasing building thermal storage that allows reducing building load up to 60% (Pfluger & Baldracchi, 2011). Moreover, Pfluger & Baldracchi (2011) also state that some historic buildings are already provided with natural ventilation systems which increase both the comfort in the indoor environment and the overall energy performance of the building. Therefore, the reuse and reactivation of these natural ventilation techniques should be always investigated.

- RES integration

Integration of Renewable Energy Sources (RES) in heritage buildings of high architectural and historical value is more restrictive than in the other buildings due to conservation demands. The most common tasks in that type of buildings are maintenance and restoration works, in which the original buildings have not formal variations. Available micro-generation equipment tends to either provide hot water or electricity, either through solar panels (hot water or photovoltaic) or from wind generators. However, these are generally useful and well-proven types of equipment and can make valuable contributions to overall energy use. Wherever the opportunity arises, small-scale hydro power can also be viable. Small-scale combined heat and power systems which have recently come to the market have great promise. Nevertheless, Pfluger & Baldracchi (2011) assume that it is intolerable to carry out tasks where the roof orientation or inclination changes, with respect to the plans of the building, and actions on façade are virtually impossible (unless whilst walls renovation), being reduced to the integration of solar roofs.

In the UK, there is a terraced house from the 19th century, which flat roof allows a collector to be hidden from ground level. Figure 16 shows the horizontally mounted collector having the least visual impact behind the parapet wall. If it is not acceptable to fix collectors to the roof, or it is not physically possible to accommodate them one alternative is to position them elsewhere – on another building, for example – with the pipes buried and routed back to the storage tank (English Heritage, 2008). Where land is abundant the collector may be mounted on the ground. An example of such a free-standing installation is in a vacancy cottage, also in the UK. The collector is mounted in the garden and surrounded by a fence, with hot water piped back to the cottage (English Heritage, 2008).



Figure 16 - Evacuated-tube solar collector on a flat roof of a 19th century house (source: English Heritage, 2008)

3.6.4 Best practices on electrical appliances and heating systems refurbishment of heritage buildings

Table 4 presents the best techniques with the slightest damage to architecture design amongst electrical appliances and heating systems consuming energy within the heritage building. It also shows the most adopted solutions into heritage buildings and an innovative solution when there is one. If any constraints arise from the solutions encountered by the multidisciplinary team, an innovative approach will be needed and defined according to every specific case. Once again, an

innovative solution is something recently available in the market prospecting greater reduction in energy consumption when compared to the solutions mostly adapted to heritage buildings. This table presents the best practices concerning electrical appliances and heating systems in order to refurbish and/or retrofit a heritage building.

Table 4 - Summary table for the best practices regarding electrical appliances and heating systems

Element	Most adopted solutions	Innovative solution	Additional information
Electrical appliances	Energy labelling on appliances is a strategy to inform users about savings in energy consumption. The rate A +++ is considered the most efficient and economic (EDP, 2012).		
Heating systems	Wet systems differ from dry systems on having hot water circulating around in radiators which radiate the heat from the water into the rooms or through under-floor coils. These systems maximise effectiveness (Change Works, 2008).	Active overflow prototype: works as a mixing ventilation approach using corridors and staircases as distribution zones. This is an advantage compared to decentralised systems with two openings per room (in and outflow) to the outside, impacting on the building structure (Rambelli et al., 2013).	In Innsbruck, Austria, where the prototype was installed, the supply air from the heat recovery system at the attic flows via the staircase and the corridors to the class rooms. The extract air is ducted from the toilets and wardrobes back to the counter flow heat exchanger to preheat the ambient air (Pfluger, 2014).
Boiler	A condensing boiler has similar components of a gas boiler but it also makes use of the heat produced during the operation which otherwise would be lost increasing its efficiency with heat recovery (Change Works, 2008).		Dwellings built in 1810 with different boiler types: non condensing of 65% efficiency and condensing of 89% efficiency (Moran, 2013).
Lighting	LED technology is possible considering the needs of conservation of spaces, efficiency and energy savings (Rambelli et al., 2013).	Luminaire “wallwasher” provides on one hand optimized visual scenery and on the other hand it should slow down the deterioration process that any material undergoes in its natural (or artificial) environment (Rambelli et al., 2013).	
Passive heating and cooling	Passive heating of buildings is possible through direct heat gain and/or thermal storage methods, that is, using transparent surfaces to gain heat and wall to storage it, making it available for the night (Givoni,		

	1991). Passive cooling is made mainly by increasing building thermal storage that allows reducing building load up to 60% (Pfluger & Baldracchi, 2011).	
RES integration	It is intolerable to carry out tasks where the roof orientation or inclination changes, with respect to the plans of the building, and actions on facade are virtually impossible, being reduced to the integration of solar roofs (Pfluger & Baldracchi, 2011).	Buildings built in the 19 th century, working nowadays as house guesting in the UK present flat roofs which allow a collector to be hidden from ground level (English Heritage, 2008).

3.6.5 Organisational measures

Upgrading historic buildings to post-1990 standards would reduce wall and roof heat loss by a factor of 50–80% (Roberts, 2008). Nonetheless refurbishing these buildings is not the first step on their conservation process. Maintenance is one of the primary principles for conservation of heritage buildings in order to preserve the existing fabric of the buildings. Also, maintenance will upgrade the status and value of the heritage buildings. Implementation of systematic maintenance works will reflect both raising interest amongst the public and the political agenda (Rashid & Ahmad, 2011). Maintenance is defined as a continuous caring performed to prevent the structure, fabric and positioning of the building which differs from the concept of repair works which is defined as the restoration or reconstruction that requires comprehensive planning (ICOMOS, 1999). Figure 17 shows the primary principles of heritage buildings conservation. First it is essential to get familiar with the condition and quality of the building. Only then, continuous caring and replacement works on the building are carried out within a maintenance plan. Finally, repair works are performed through refurbishment and/or retrofitting interventions. This plan is sequential since it is impossible to change a building without acknowledging its history. That is to say that the first requirement is problem recognition as it is in Mickaitytė et al. (2008) model. Only then, the proposition of a maintenance plan is possible after looking for solutions with consequent decision making – phases 2 and 3 of Mickaitytė et al. (2008) model. Finally, corresponding repair works to execution of the plan previously proposed: phase 4 of Mickaitytė et al. (2008) model. Since the subject tackled in this research is the refurbishment of heritage buildings, as Mickaitytė et al. (2008) model states, it is possible to link it with the primary principles of heritage buildings conservation.

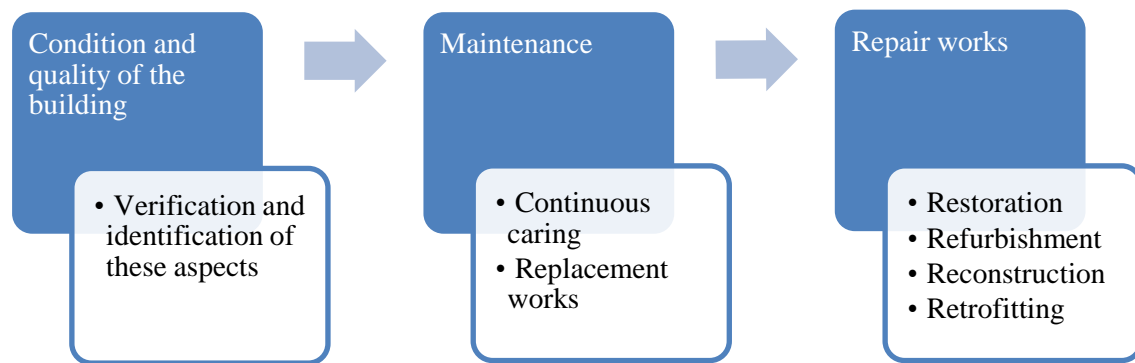


Figure 17 - Primary principles of heritage buildings conservation

However, a maintenance program in heritage buildings is still lagging in many cases and some of the major issues contributing to that are as follow (Rashid & Ahmad, 2011):

- The absence of the application of a scheduled or periodic inspection by the responsible authorities is the main reason for the decaying condition of heritage buildings. The main work carried out on these buildings is mainly repair and replacement which concern the services systems and not the building fabric or the structural elements.
- Some of the responsible organisations and entities of heritage buildings do not include a proper set-up for maintenance unit to carry out this specific work.

- The financial incentives given to the entities responsible to carry out maintenance works in heritage buildings are limited. Additionally, the financial allocation provided by governments is only for selected buildings.

3.6.6 Best practices on organisational measures in heritage buildings

The execution of the maintenance works in historic buildings should not be taken lightly. The works require involvement of experts in order to ensure quality and to prevent the loss of heritage value. Finding the best practices on organisational measures in heritage buildings may be a difficult task to accomplish. Therefore it is necessary to overcome the issues preventing the implementation of a maintenance program:

- ✓ Inspection by the responsible authorities focusing in the building fabric and structural elements should be scheduled or periodic.
- ✓ A set-up for maintenance unit to carry out this specific work should be included by the responsible organisations and entities of heritage buildings.
- ✓ Financial incentives given to the entities responsible to carry out maintenance works in heritage buildings should be more attractive and extensive.

After verifying and identifying the condition and quality of a heritage building, a maintenance program should be proposed and, afterwards, its retrofitting and/or refurbishing performed. There are practices to take into account when it comes to the implementation of refurbishment and retrofitting solutions. They can be considered as rules of thumb when a refurbishing and/or retrofitting process is planned and are as follow:

- It is key to know the importance of the buildings and its inside treasures (fixtures, fittings or features) previous to start planning an intervention.
- A variety of options (from the most applied solutions to an innovative one) should be considered before defining the one for improving performance and environmental sustainability.
- Data gathering regarding relevant characteristics of the building under study, such as historical use, goal, energy use bills and occupation of the building is crucial to understand the way forward.
- The participation of various and expert identities, comprising a multidisciplinary team of engineers, architects, historians, policy makers, etc., will provide the most complete data gathering possible.
- Minimise the physical and visual impact of any work or new equipment refers to the need of keeping the architectural design as little as possible changed. As an example, after being retrofitted, the original image of Bernardas' Convent in Lisbon both inside and outside still stands (Martins & Carlos, 2013).
- At the same time, the smaller details into historical fabric such as frames, windows or adornments on the walls should also be intervened as little as possible to prevent their damage. For example, to preserve the historical artefacts within a heritage building in Ottawa, Canada, the indoor air conditions specified are a temperature of 21°C and a

relative humidity (RH) of 35% in the winter and 50% in the summer. It is also desirable that short-term (daily) variations in RH are no greater than 5% because high humidity can compromise the life of the building envelope and artefacts (Saïd et al., 1997).

- Techniques that were previously proven to work in historic buildings are a secure decision. Nevertheless, new materials and systems should also be considered and implemented – so innovation occurs.
- The use of modern materials, if essential, needs to be based upon an informed analysis where the implications of their inclusion and the risk of problems are fully understood (English Heritage, 2012d).
- As heritage buildings need to breathe, the use of vapour barriers and many materials commonly found in modern buildings must be avoided when making improvements to energy efficiency, as these materials can trap and hold moisture and create problems for the building (English Heritage, 2012a).
- Micro-generation equipment can be beneficial for the energy performance of historic buildings. However, if they cause impact on the character and appearance of buildings their installation is intolerable. Figure 16 shows that it is possible to introduce micro-generation equipment in a heritage building without affecting its historical value (English Heritage, 2008).
- By the end of planning a refurbishment and/or retrofitting intervention, it is crucial to consider how the changes can be reversed without damaging the existing fabric. If something does not go according to the plan, if the heritage value is at risk, there must be a reversed solution. Pfluger (2014) states that the reversibility of planned interventions could be divided in two groups: a) the technical measures like ventilation or lighting system that can be dismantled and wall perforation could be blinded and b) the internal insulation that can be dismantled as well but the interior surfaces would need a complete reconstruction.

Throughout this chapter it was recognised that it is the fundamental the safeguard of the individual character of historic buildings and the local distinctiveness. However, sustainable design objectives can be achieved without compromising the buildings still standing (Godwin, 2011). There are retrofitting and/or refurbishing solutions to consider pleasing all the parts involved.

4 Methods

Heritage buildings present low energy performance. Refurbishment and retrofitting come as solutions in order to lower their energy use. However, it is important to ensure that historic properties are comfortable and suitable for contemporary lifestyles and to new purposes. Chapter 2 discussed the different functional characteristics between heritage and modern buildings. Chapter 3 examined the available solutions when historic buildings need to improve their energy efficiency. This research was performed through a comparative case study analysis. In order to complement the theoretical findings from previous chapters empirical data was gathered. This chapter explains how the empirical data was gathered and analysed. Section 4.1 describes the sample of heritage buildings consisting on three case studies and section 4.2 explains the conducted method: a comparative analysis.

4.1 Sample

This research is part of the European funded project “Reducing Footprints of Monumental Structures, Landscapes and Buildings (ReFoMo)” that explores the potential and demand for restoration projects which would improve the energy efficiency of heritage buildings. ReFoMo is an effort of three countries:

- i) Historic fortresses in Utrecht (Netherlands);
- ii) Historic public buildings/ iconic buildings in Bologna (Italy);
- iii) Industrial heritage in Budapest (Hungary).

These three buildings were chosen to study the phenomenon of their energy performance in depth. Each one was analysed in its specific context and in greater detail. Therefore, a case study approach was taken to answer the main research question: “how to improve the energy performance in heritage buildings?”.

A case study is an appropriate way to answer broad research questions by providing a thorough understanding of how the process develops (Swanborn, 2010). Case studies aim at detailed description, at uncovering a phenomenon that is situated in the context of a research. The cases were studied in its natural surroundings maintaining the original setting. They were chosen in view of its relevance to the project. In a qualitative research the sampling is usually delimited (in advance) by certain criteria in such a way that all the cases may be integrated in the study (Flick, 2006). In this research, the criterion was heritage buildings requiring improved energy performance through retrofitting and refurbishment interventions.

4.2 Comparative analysis

A comparative case study is defined as a tool of analysis that focuses into similarities and contrast among cases. It can contribute to the inductive discovery of problem solving and to theory building (Finifter, 1993). Using more than one case study enabled this research to

explore differences between cases. A case study enables to gather data from a variety of sources and to converge the data to illuminate the case (Mills et al., 2006). The information gathered about the case studies was mainly obtained by reading the feasibility studies prepared by each partner of ReFoMo project. Moreover, some data was collected during informal and personal meetings with different team members.

By comparing different historic buildings in Europe, it is expected to find common facts to all cases or a solution that can be shared by all in order to make an energy efficient refurbishment and/or retrofitting of a heritage building. Although it is acknowledged that each heritage building is unique and therefore it needs customized energy solutions, this research aims at understanding if different retrofitting and/or refurbishing technologies and solutions are applicable under different circumstances. It is through the comparison of the case studies that the understanding will be achieved. A comparative analysis was the selected method in this research as the case studies represent three geographical areas (North, Central and Southern Europe) in different climate zones and socio-cultural settings and distinctive building types (fortresses, public buildings and industrial heritage).

Since the goal of comparative research is to replicate findings across cases, research needs equivalent definitions to measure constructs (Baxter & Jack, 2008). There is a procedure that needs to be followed to ensure coherency and consistency. Therefore, a comparative analysis through DMAIC approach was conducted. The DMAIC approach was selected to compare the three case studies because it focuses on improving existing processes that have not reached an optimal state (Desai & Shrivastava, 2008). It is an approach to improve a process consisting of the following steps:

- 1) Define;
- 2) Measure;
- 3) Analyse;
- 4) Improve;
- 5) Control.

Figure 18 shows how all the phases are linked together (Rath & Strong, 2000). The strength of DMAIC approach is the way in which a specific case is structured and analysed. Its rigour and structured methodology are the main differences between DMAIC approach and other process improvement techniques (Kumar et al., 2006). The core idea behind DMAIC approach is that if it is possible to measure how many defects there are in a process, it is possible to systematically figure out how to eliminate them and get as close to zero defects as possible (McKay & Shank, 2008). In other words, considering energy inefficiency as a defect, DMAIC approach allows to search for causes of that defect and its solutions. Through DMAIC approach, that clarity of thoughts is given allowing the proposition of measures that would eliminate those sources of energy inefficiency. The five steps of the DMAIC approach are explained in the following.

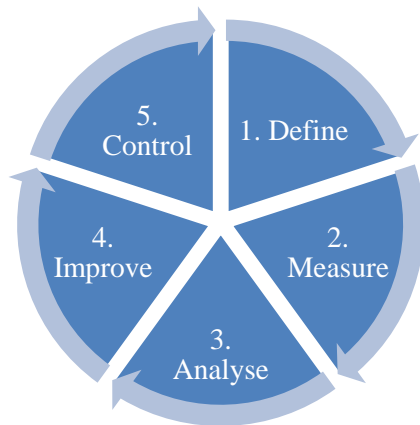


Figure 18 - DMAIC approach (source: Rath & Strong, 2000)

- “Define” is the first phase. Here, the purpose and scope of the project are defined. Background information on the process is collected. The output of this phase is a clear statement of the intended improvement and a list of what is important to the costumer.

In the case of this research, a general description of each case study was given during this step. As studied in sections 3.6.1 and 3.6.3, the parameters to define during the description phase are those related to: i) building envelope and ii) electrical appliances and heating systems.

- “Measure” is the phase where a current baseline should be established. Namely, what parameters are to be measured and how they will be measured.

Concerning this research, it is explained the type of energy audit carried out and which key parameters were assessed in each building. An energy audit gives a baseline of the building drawing the energy performance of the building, for example, energy use values and “U” values of the elements of each building.

- “Analyse” is the phase that develops theories of origin cause(s), confirm the theories with data and finally identify the root cause(s) of the problem. The verified cause(s) will form the basis to start searching for solutions.

Regarding this research, once the energy audit is done, the data is analysed. Based on the energy performance, the multidisciplinary team propose a detailed description of the actions and plan to refurbish and/or retrofit each building.

- “Improve” refers to the identification, testing and implementation of possible solutions to the problem; in part or in a whole.

In the case of this research, the different steps followed towards an actual implementation of measures that would improve energy performance during the process of refurbishment and retrofitting of each building were described.

- “Control” phase is the phase where improvements are monitored to ensure the continuity of the solutions. During this step the creation of a control plan, the updating of documents and business process is required.

Respecting the three case studies, there is information required such as monitoring and maintenance plans to follow in the future, different behaviours or policies to be adapted. Insights into future plans/strategies to be implemented by each partner were found.

A DMAIC approach was carried out in each of the case studies. Then the three case studies were compared under each of the phases of DMAIC. The analysis of the results obtained by this method were compared with the theoretical findings explained in chapter 2 and 3 in order to complement the best practices aimed at an energy efficient refurbishment of heritage buildings. Figure 19 shows the method followed in order to answer the main research question.

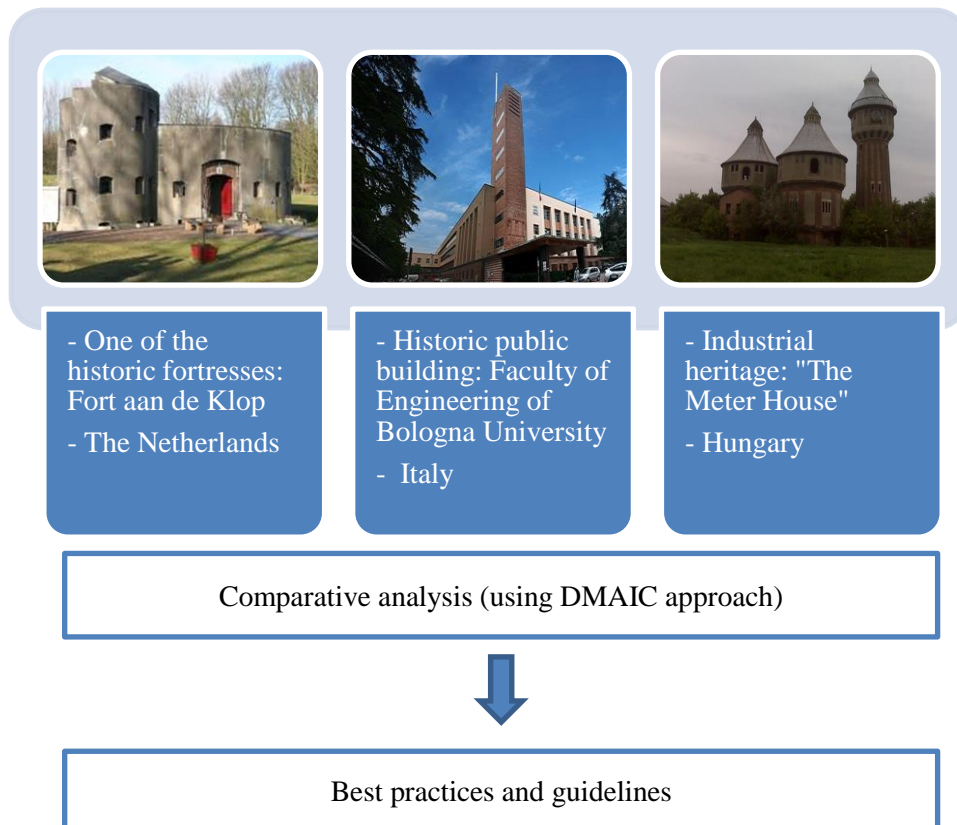


Figure 19 - Methodology followed to answer the research question: “How to improve the energy performance of heritage buildings?”

The three case studies are described in chapter 5.

5 Results

Heritage buildings are part of the identity of a community and the history of a city. Through this thesis it was seen that – in Europe – its energy performance and thermal conditions require improvement due to the high standards of contemporary times. Chapter 2 discussed the characteristics of heritage buildings. Chapter 3 presented possible retrofitting and/or refurbishment solutions that could be applied for these specific buildings. Chapter 4 described the method followed to give an answer to the main research question: “How to improve energy performance in heritage buildings?”. The present chapter presents the results of the feasibility studies described in section 4.1. It is organized under each of the DMAIC phases in each section a comparison among the case studies is executed⁶.

5.1 Define phase

As explained in 4.2, “define” phase gives a general overview of the relevant characteristics of each building. This concerns the history, architecture, present situation of the building and purpose of retrofitting and/or refurbishment.

5.1.1 Historic fortresses in Utrecht (Netherlands)

The New Dutch Waterline (NHW) is an historic defence line consisting of a network of dykes, sluices with over 85 kilometres extension. Combined with 50 fortresses and castles, the military line worked as a protective ring of 3–5 km wide defending the western part of the Netherlands around the cities of Amsterdam and Utrecht in the 19th century. In case of an emergency a large area could be flooded with 40 cm of water by breaking dykes and dams, making it impossible for soldiers and their cargo to advance further inland. Nowadays, the New Dutch Waterline no longer serves a military purpose and holds a protected status as a National Heritage Site and a National Landscape (AT FORT, 2012). In 2000 a plan was established in order to redevelop the waterline and give it a newer use. Sustainability was an important aspect here, i.e. viability of renewable energy production, biodiversity conservation and water retention (Dam et al., 2012).

In this research two fortresses were analysed: Fort de Gagel and Fort aan de Klop. New functions are envisioned for both fortresses. These new functions intend to be compatible with the use of technology solutions for better energy management through retrofitting and/or refurbishment processes.

- Fort de Gagel

The construction of Fort de Gagel started in 1819 but only in 1875 its definitive form was realised. Initially this fort existed from L-shaped earthen walls with places for the guns,

⁶ At the moment when this thesis was written, the information gathered regarding the case of Faculty of Engineering consisted only of a report dated April 2014. The information about the “Meter House” was provided on the final report to ReFoMo dated August 2014. The data gathered concerning both fortresses were gathered in October 2014.

surrounded by a moat. Starting from 1848 the fortress has been substantially amended. Between 1850 and 1852 on the city side the defensive structure was built (bomb-proof guardhouse), with walls of 1500 mm thick masonry. The ground floor is of stone and partly of wooden beams with wooden floors. The first floor is entirely made of wooden beams with wooden floors. Fort de Gagel has single glazed windows that are set back 400 mm from interior shutters. The roofs are integrated in defensive wall, i.e. covered by earth and vegetation. About 1880, the fort was again improved (rebuilt at the inner site). The moat around the guardhouse was partially muted, after which the bomb-proof barracks and depot were built. In the first half of the 20th century the wall was partially excavated. In the years 1935-1940 three group shelters of reinforced concrete were built on the outer slopes. After World War II, Fort de Gagel was used for the last time for military purposes and the trenches situated between the group shelters were muted. Additionally, the entries of the Group shelters are closed with brickwork. The guardhouse is now entirely in the condition of 1880 and to all sides with shoot-holes oriented on the Gagel dyke. Nowadays, the barracks function as offices and are of 1000 mm thick. Offices are located on the first floor of the southwest facade allowing natural lighting. Appliances in use include computers, printers and other office appliances related to standard office use. Regarding the heating system, the barrack building has newly installed radiators and central heating system consisting of a heating boiler and water (electrical) boiler.

Since 1971, Fort de Gagel is governed by the policy principles of the municipality of Utrecht, the provincial government of Utrecht and the central government. On one hand, these entities aim at preserving the cultural-historical, monumental, civil engineering and military-historical assets of fortresses. On the other hand, it is also intended to enhance the landscape and wildlife value achieving sustainable development. Only minor renovations such as wooden floor restoration to its original design and heating systems installation took place in the periods 1960/70 and 2000/2010. Figure 20 shows the current state of the fortress.



Figure 20 - Fort de Gagel (source: Tersteeg, 2014)

Besides its existing use, it is envisioned to work as an information centre, offices (as current situation), café-restaurant and centre for outdoor activities. Visitors will be able to get something to eat and drink in a typical 19th century fortress. Also cycling and cannoning will be a possible way to get there. At the same time the aim is reducing the footprint and energy consumption of the buildings (M. Bonnike, personal communication, October, 2014).

- Fort aan de Klop

The construction of Fort aan de Klop began in 1819. The guardhouse was built between 1850 and 1852. Redesigning occurred twice: in 1900 and in 1913. The whole fortress was renovated in 2007. Figure 21 shows the current exterior aspect of the fortress. The guardhouse represents the defensive structure with 1500 mm of thick masonry. It has single glazed windows, solid floors and flat roof, housing a restaurant and a kitchen. In the guardhouse windows are set back 400 mm so the walls work as shading devices. Besides the guardhouse there are barracks consisting in group accommodation and other buildings. These barracks were renovated between 2005 and 2007 consisting of wooden insulated walls, equipped with general double glazed glass and exterior window shutters of historic design. The lighting system consists of halogen and low energy light bulbs and the appliances in use are reported as standard restaurant appliances (M. Bonnike, personal communication, October, 2014). The guardhouse is heated by radiators (being a gas boiler the source) while some of the barracks are heated through floor heating. Other measures already implemented include: i) water saving shower heads; ii) modern toilets with dual flush; and iii) a small kitchen garden with some herbs.

The purpose of the renovation in 2007 was to build a restaurant in the old guardhouse while renovating the exterior and interior of the guardhouse. Furthermore, the bat habitat in the basement was created and preserved. The purpose of renovating de Fort aan de Klop within this project is to create an energy efficient and sustainable building while making the fortress even more attractive for visitors.



Figure 21 - Fort aan de Klop (source: Janssen, 2012)

5.1.2 Historic public buildings/ iconic buildings in Bologna (Italy)

The School of Engineering of the University of Bologna was the building selected by Italy to integrate ReFoMo project. The historical value of this building restricts the possibilities for adjustment and retrofitting. Since they are part of the identity of a city and a community,

heritage buildings obey to strict laws from different entities when renovations are being considered. However its energy management is difficult due to different functions and rooms in a broad range of sizes (Garai et al., 2014). The School of Engineering and Architecture of Bologna is composed by 4 building as Figure 22 shows:

- Building 1⁷: the historical main building of the Faculty of Engineering built in 1935.
- Building 2: Building built later in the 1980's.
- Building 3: Building built in the 1980's.
- Building 4: Building built after 1935 having the same building materials of building 1.



Figure 22 - The buildings composing the School of Engineering and Architecture of Bologna (source: Garai et al., 2014)

The construction of the School of Engineering in Bologna is the result of a process followed from 1875 until 1931. The official start of the school for engineers was in the 1935. Figure 23 shows the building under study (building 1: the main building of the Faculty of Engineering). The drawing classrooms are the most used and attended rooms during the day by students and are oriented to north-northeast, equipped with continuous windows that completely opened ensures lighting and ventilation throughout all day. The lighting has also been studied and especially in relation to the orientation of the classrooms so the insolation is always comfortable for the students. In order to allow the continuity of the glass, the pillars in the classrooms are set back of about a meter compared to the windows. The empty space between the windows and the pillars was used to place the ducts for the heating of the classrooms.

The historic building is constituted by a structure in the frame of reinforced concrete and pillars with average thickness of 350 mm. The frame structure is covered with a brick cladding on the ground floor, while a layer of plaster on the upper floors. The floors are of mixed type and drilled in concrete, in most slabs with brick, sound-proof. The opaque walls have a thickness between 600 and 800 mm and are masonry brick with an air gap. Close of the windows the thickness of the walls is reduced significantly, with a thickness from 200 to 400 mm. The emblematic eight-story library tower, 45 meters high, is an unheated thermal zone, located at the main entrance of the building. It is completely covered with brick which is detached from the walls of the plaster building in the main pillars covered in travertine honed.

⁷ From now and onwards, every time it is written Faculty of Engineering it is referring to “The building 1”.

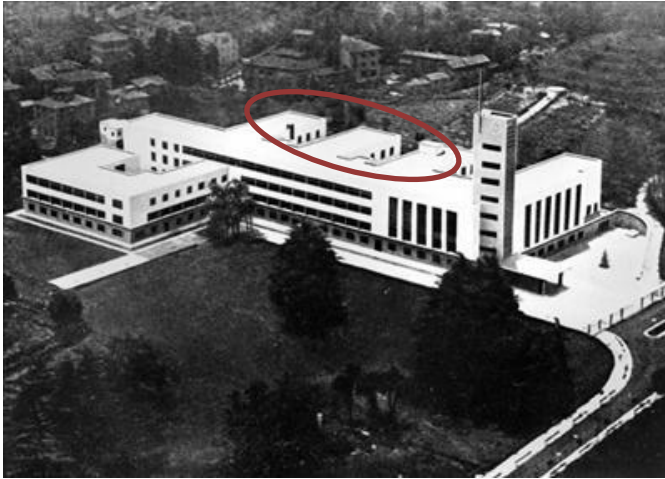


Figure 23 - Building 1: the historical main building of the Faculty of Engineering (source: Garai et al., 2014). The drawing classrooms are encircled.

The gas heating plant is in the basement, in a central position with respect to the heated volume and with natural circulation. The heating layout consists of: central system with three gas boiler, a heating boiler and a heat pump. The distribution system is made of non-insulated pipes placed in the walls, the vertical pipes connecting the radiator positioned at the various levels.

5.1.3 Industrial heritage in Budapest (Hungary)

In early 1900's, the growing residential gas consumption in Hungary, required the establishment of a new gas plant instead of several smaller coal gas plant capable of supplying the capital. The availability of road and railway transport was important, as well as the possibility to connect it to the waterway. Furthermore, sufficient spaces for service and storage buildings were factors to take into account while choosing the location of the new plant. By 1940, the gas plant had reached the maximum of its capacity, so developments were initiated. However, it reached its production limits again by 1942, but further developments were stopped during World War II. In accordance with the changeover to natural gas in 1960, processing plants were built, with the aim of further increasing the capacity. In 1980 a decline process started with the deterioration of furnaces causing severe problems in the equipment. Thus, in 1984, coal based gas production ceased at the "Meter House". The purification of gases produced waste that was first handled and stored improperly. Then, after it was declared hazardous waste in 1982, the gas plant waste was put into two in-situ concrete containers. All that was left outside the containers remained in the ground and ground water. Besides manufactured gas plant waste, several types of hydrocarbon derivatives were deposited on the territory, affecting the environment with an unpleasant smell. In 1994 the building gained protected status. In 2009 removing hazardous waste from the gas container foundations was the first important step in the process of cleaning the territory.

Buildings within the plant are ordered into two groups according to their appearance. Industrial buildings which made with timber-framing-style walls reinforced with steel girt. The second group of buildings is characterized for carrying historical marks with brickwork cladding. This group demands more energy use due to their functions as administrative building, welfare

buildings and housing estate. The “Meter House” was the selected building to be refurbished and or/ retrofitted. The “Meter House” was built in 1914 and is one of the most valuable buildings of the factory complex in terms of heritage aspects (Figure 24). It was used for measuring different gases. It has a symmetrical, long rectangular and solid floor plan, dual-pitched roof and red and yellow brickwork facade, without shading. The facades are divided into sections with groups of two or three slender, vaulted single windows between them. The existing external walls are made of small-size clay bricks of varying thickness with plaster finish on the inner side. The interior of the ground floor constitutes a continuous space with open steel roof structure. The “Meter House” currently functions as storage site for stones, using no energy. Establishing a Contemporary Cultural and Communication Centre, suitable for large masses and perform various functions is the aim of the refurbishment process. Through this form of utilization, the building will be accessible to a wider audience and its operation will become also more efficient.



Figure 24 - The “Meter House” (source: Alexa et al., 2014)

5.1.4 Comparison

As explained in section 4.2, the comparative analysis of “define” phase is related to: i) building envelope and ii) electrical appliances and heating systems. Table 5 shows the relevant parameters that define each case study.

Table 5 – “Define” phase comparison

	Fort Gagel, Utrecht, The Netherlands	Fort aan de Klop, Utrecht, The Netherlands	Faculty of Engineering, Bologna, Italy	The “Meter House”, Budapest, Hungary
Building envelope	<ul style="list-style-type: none"> - 1819 Guardhouse - Walls of 1500 mm thick masonry. - The roofs are integrated in defensive wall, i.e. covered by earth and vegetation. - Floor is of stone and partly of wooden beams with wooden floors. - Single glazed windows. <p>Barracks</p> <ul style="list-style-type: none"> - Walls of 1000 mm thick masonry. - Good artificial lighting due to orientation. <p>Purpose of refurbishment: An information centre, offices (as current situation), café-restaurant and centre for outdoor activities.</p>	<ul style="list-style-type: none"> - 1819. Guardhouse - Walls of 1500 mm thick masonry. - Flat roof. - Solid floors. - Single glazed windows. <p>Barracks</p> <ul style="list-style-type: none"> - Wooden walls. - Double glazed glass windows and exterior window shutters of historic design. - Floor is solid including floor heating system. <p>Purpose of refurbishment: - Create an energy efficient and sustainable building while making the fortress even more attractive for visitors.</p>	<ul style="list-style-type: none"> - 1935. - Structure of reinforced concrete and pillars with average thickness of 350mm, covered with brick cladding on the ground floor and plaster on the upper floors. - Floors are of mixed type and drilled in concrete, in most slabs with brick, sound-proof. - Opaque walls of masonry brick with thickness between 600 and 800 mm with an air gap. <p>Purpose of refurbishment: - Improve difficult energy management due to different functions and rooms.</p>	<ul style="list-style-type: none"> - 1914. - Brickwork cladding facade. - Dual-pitched roof, clad with red and yellow brickwork. - External walls of clay bricks of varying thickness with plaster finish on the inner side. - Open steel roof structure. - Single glazed windows. <p>Purpose of refurbishment: - Establishing the Contemporary Cultural and Communication Centre, suitable for large masses and perform various functions is the aim of the refurbishment process</p>
Electrical appliances and heating systems	<p>Barracks</p> <ul style="list-style-type: none"> - Appliances in use are of standard office use. - Heating boiler and water (electrical) boiler. 	<ul style="list-style-type: none"> - Halogen and low energy light bulbs are used. <p>Guardhouse</p> <ul style="list-style-type: none"> - Appliances are of standard restaurant appliances. - Central heating on gas. <p>Barracks</p> <ul style="list-style-type: none"> - Some of the barracks are heated through floor heating. 	<ul style="list-style-type: none"> - Lighting and proper ventilation ensured throughout all day due to orientation. - The heating plant system consists in: central system with three gas boiler, a heating boiler and a heat pump. 	<ul style="list-style-type: none"> - No energy use.

Starting by comparing the building envelope of the case studies, it is clear that the construction period differs. The fortresses are approximately a century older than the other two buildings. Between the two fortresses differences arise when comparing the barracks. The barracks of Fort aan de Klop went through a recent renovation. Therefore, these barracks present better energy performance and thermal comfort: wooden insulated walls, double glazed windows and exterior window shutters, insulated roof and solid heated floor. In contrast, the barracks from Fort de Gagel have walls of 1000 mm thick masonry. Older structures as fortifications present thicker walls than more recent buildings. When comparing the walls among all the buildings there is something to emphasize regarding the structure design. The fortresses only present walls while the Faculty of Engineering and the “Meter House” present a structure/frame (pillars) additionally to walls.

The fortresses have walls of 1500 mm thick masonry. The Faculty of Engineering has a structure of reinforced concrete and pillars with average thickness of 350 mm, covered with brick cladding on the ground floor and plaster on the upper floors. “Meter House” has brickwork cladding facade. Additionally, the Faculty of Engineering has opaque walls of masonry brick with thickness between 600 and 800 mm with an air gap. The external walls of “Meter House” are of clay bricks of varying thickness with plaster finish on the inner side. Even though the walls of more recent buildings are composed by more than one element (brick with air gap or clay brick with plaster finish), the walls of the fortresses are thicker. Another interesting aspect is the fact that Italian and Hungarian buildings both present an integrated layer of insulation: brick with air gap in the Faculty of Engineering and a plaster finish on the inner side of the clay bricks in “Meter House”. These features show that at the time of the construction, the architects and engineers of both buildings thought about insulating them. In the future, the need for insulation will be reduced when compared to the fortresses. The majority of windows are single glazed so retrofitting might be suggested.

Regarding the electrical appliances and heating systems, only the fortresses present standard appliances in use. Fort de Gagel has appliances used in offices. Fort aan de Klop has appliances used in restaurants. The heating system in use in Fort de Gagel consists of a gas boiler plus a water (electrical) boiler whereas in Fort aan de Klop is central heating on gas. Concerning the heating system in the Faculty of Engineering, either gas or electricity is consumed. The heating distribution system in Italy is made of non-insulated pipes and there is no temperature control in individual rooms. The industrial building in Budapest currently uses no energy functioning as a storage site.

5.2 Measure phase

“Measure” phase discusses the current parameters that lead to the ongoing energy performance of the different heritage buildings. It was argued in section 3.2 that the best way to collect these parameters is through an energy audit. Therefore, the energy audits performed in each building were the focus.

5.2.1 Historic fortresses in Utrecht (Netherlands)

M. Bonnike (personal communication, October, 2014) used data from reports from Tersteeg (2014) about Fort de Gagel and Janssen (2012) relating to Fort aan de Klop. These documents reported energy use calculations and consequent financial impact. The energy calculations are: “U” values and information with respect to the energy use were calculated using software (RETScreen) by De Groene Grachten. This data is analysed in 5.3.1.

5.2.2 Historic public buildings/ iconic buildings in Bologna (Italy)

In order to highlight the zones with thermal discontinuity (thermal bridges) of the external envelope, a thermography was carried out in Faculty of Engineering in Bologna. This data is shown in 5.3.2.

5.2.3 Industrial heritage in Budapest (Hungary)

The “Meter House” currently functions as a stone material deposit. Consequently, there is no energy required for cooling or heating. Furthermore, the Hungarian case study relied on the feasibility study made by BVV zrt. in September 2013 suggesting the realization of a Contemporary Cultural and Communication Centre capable of accommodating larger groups of people (Alexa et al., 2014). Energy calculations were made based on the HVAC systems. No energy audit was performed on the building. The assumed normal operating conditions for the “Meter House” currently consist in: i) a gas boiler for heating with estimated efficiency factor of 80% (Alexa et al., 2014); ii) panel heaters with thermostatic valves; iii) air handling units which include only supply sections to ensure the fresh air supply; iv) individual fan systems for exhaustion without heat recovery; v) an external compact chiller unit to ensure cooling.

5.2.4 Comparison

As discussed in section 5.3.1, an energy audit for heritage buildings should focus on the three topics: i) building envelope; ii) electrical appliances and heating systems; and iii) organisational measures. For this reason, Table 6 is divided into those three topics showing that different methods can be used to perform energy audits of the historical buildings under study.

Garai et al. (2014) performed a thermography using an IR camera in order to obtain pictures to analyse local heat losses, assessing the effectiveness of insulation. This technique is included in the best practices of diagnostic and monitoring tools to evaluate energy performance of heritage buildings (see 3.5.2). A thermography offers the advantage of accurate and complete results to the “analysis” phase via a practical test to evaluate energy performance. Since it was part of an energy audit, by performing a thermography the auditors were able to observe and highlight thermal bridges of the building envelope. In the case of the Dutch fortresses, M. Bonnike (personal communication, October, 2014) resorted to a report with energy use values to simulate

the fortresses structures on RETScreen software. The outcome of the simulation was a set of “U” values of the building envelope. Alexa et al. (2014) explained that no energy audit was performed at the “Meter House”. Instead, they decided to perform energy calculations. These calculations included coefficient heat transmission of the building envelope structures and the total energy need of the building (heating, cooling, ventilation and lighting).

The information, regarding the topic of organizational measures, was unavailable at the moment of writing this report. As part of the organizational measures, it was expected to know the energy management plan and the maintenance plan being carried out. For example, it would be important to know the daily operation of the appliances used in all buildings under study. In this way, it would be known if the buildings are on a time of use tariff paying a different price for their electricity during different time periods (peak or off peak time)⁸. Also, a lighting profile can be necessary to highlight unnecessary energy use.

If the different parties concerned with the energy efficiency of heritage buildings considered applying retrofitting measures, it is compulsory that an energy audit is carried out as the first step of the retrofitting process (see 3.5.1). Performing an on-site survey is the second step within an energy audit so there is a professional assessing the building determining how energy efficient is the overall structure. ReFoMo can benefit from energy audits. The Italian case study performed an energy audit even though it was incomplete. The first step of an energy audit is gathering data regarding the energy use and those detailed values were missing. However, the results drawn by the thermography identified causes of energy inefficiencies linked to the building envelope. Therefore, Garai et al. (2014) knew what they needed to retrofit at building envelope level. Additionally, since it was also described the heating system it was also possible to suggest retrofitting of this component. On the other hand, there was no energy audit performed at the fortresses or at the “Meter House”. M. Bonnike (personal communication, October, 2014) and Alexa et Al. (2014) chose to analyse previous reports about the energy use of the buildings and to run software simulations to derive “U” values. Their results allowed them to suggest retrofitting solutions but an energy audit would allow more knowledge about the buildings under study. In chapter six it is discussed the key parameters that will lead to an energy efficient retrofitting of these heritage buildings.

⁸ Peak electricity is provided during set times of the day when demand for electricity is highest. At these times, the power system is stretched to its limits. Off-peak electricity is provided during set times of the day when homes and businesses use less electricity. To encourage people to use electricity during these times of the day, many providers offer cheaper electricity during these off-peak times.

Table 6 – “Measure” phase comparison

	Fort Gagel, Utrecht, The Netherlands	Fort aan de Klop, Utrecht, The Netherlands	Faculty of Engineering, Bologna, Italy	The “Meter House”, Budapest, Hungary
Building envelope	RETScreen software simulation.		Thermography.	
Electrical appliances and heating systems	Tersteeg (2014)	Janssen (2012)		Energy calculations based on the HVAC systems required for the use described in a feasibility study (executed earlier by the owner of the site).
Organisational measures	No information focused on this topic was available. However, a number of measures can be audited in order to understand the energy use of the building. For example: the use of lights, appliances or natural lighting can be monitored by surveys, observation or smart monitoring (smart meters) when installed. These measurements may give an indication of how efficient the use of the different appliances is.			

5.3 Analysis phase

“Analysis” phase discusses the actual state of the building in terms of energy performance based on the data gathered in the “measure” phase. Through the results of the energy audit it is possible to understand which elements require retrofitting and/or refurbishment processes to improve energy performance in each building under study.

5.3.1 Historic fortresses in Utrecht (Netherlands)

M. Bonnike (personal communication, October, 2014) analysed the report by Tersteeg (2014) about the Fort de Gagel and the report by Janssen (2012) related to the Fort aan de Klop. She noticed that at Fort de Gagel the walls in the guardhouse and in the barracks are uninsulated. Another aspect that was found is that the working spaces need additional lighting at a minimum because in winter natural lighting is insufficient. In the hallway, the light is on all day so a solution has to be proposed to prevent lighting use when it is unnecessary. Fort aan de Klop also presents uninsulated walls in the guardhouse. However, as referred in 5.1.1, its barracks were renovated installing walls and windows insulation. Due to value protective reasons possibilities passive heating and cooling including external sun shading are doubtful. On the other hand integration of passive heating seems to have good potential.

As explained in 5.3.1, simulation run in RETScreen software delivered data concerning “U” values. These values are presented in Table 7:

Table 7 - “U” values of both fortresses (source: M. Bonnike, personal communication, October, 2014)

Thermal transmittance (W/m²K)	Fort de Gagel	Fort aan de Klop
“U” value max single glazing	5,7	5,7
“U” value max double glazing	3,3	3,3
“U” value walls (barracks)	1,16	0,82
“U” value roofs (barracks)	2,08	1,03
“U” value floor	0,47	0,47

Comparing these results with those in Table 1 (see 2.1), it is noted that the “U” values of both fortresses are higher than the typical values for heritage buildings regarding single glazing, double glazing and floor. One reason for that might be the willingness to preserve (some of the) original windows and floor from the beginning of 19th century. Both fortresses have specific building elements with a high historical value of a specific period. Maintaining those historical features may imply no improvement in energy performance and thermal comfort. The walls of Fort de Gagel show approximately the same “U” value as of a typical heritage building (despite the difference between the thicknesses considered). The walls of Fort aan de Klop show a lower “U” value compared with Fort de Gagel due to their insulation. The roof of Fort aan de Klop also show a lower “U” value compared with Fort de Gagel due to their insulation. However, the roofs of both fortresses cannot be compared to typical values because both fortresses present flat roofs unlike the typical value which considers pitched roofs.

As explained in 5.2.1, gas and electricity use values were also described⁹. At Fort de Gagel, gas use is twofold: space heating and water heating (3900m³). Electricity is used mainly for heating (9000 kWh) and lighting (4900 kWh). At Fort aan de Klop gas was used to space heating, water heating and for cooking (9500m³). Concerning electricity, kitchen was the main user (30000 kWh) and cooling was the second one in the guardhouse (16000 kWh).

5.3.2 Historic public buildings/ iconic buildings in Bologna (Italy)

The current energy management system at Faculty of Engineering monitors the switch-on and switch-off of the heating system during the winter season. In 2012, the gas consumption was of 473.237 m³. However there are no devices or automatic temperature control in individual rooms so control and monitoring need to be implemented. The insulation of the distribution pipes in the thermal power station is in good condition therefore no retrofitting is envisioned. On the contrary, along the majority of the distribution network insulation is not present. Uninsulated distribution network means that heating is not efficiently distributed – there are losses of heat along the way. Thus, insulation of these pipes needs to be considered.

Figure 25 shows a photo of the facade of the Faculty of Engineering on the left and an infrared photo of the same façade taken with an infrared camera on the right. The infrared highlights the thermal bridges and the different insulation of the building. In the figure thermal bridges are detectable through different colours: red is the warmer and blue is the colder. The higher the temperature, the faster the heat loss. By observing the infrared picture it was noted that the temperature is higher in the reinforced concrete frame than it is in the walls. Also, the frames of the windows revealed to be warmer than the walls. Better insulation of the frames could help to improve the storage of heat inside thus better thermal and energy performance.

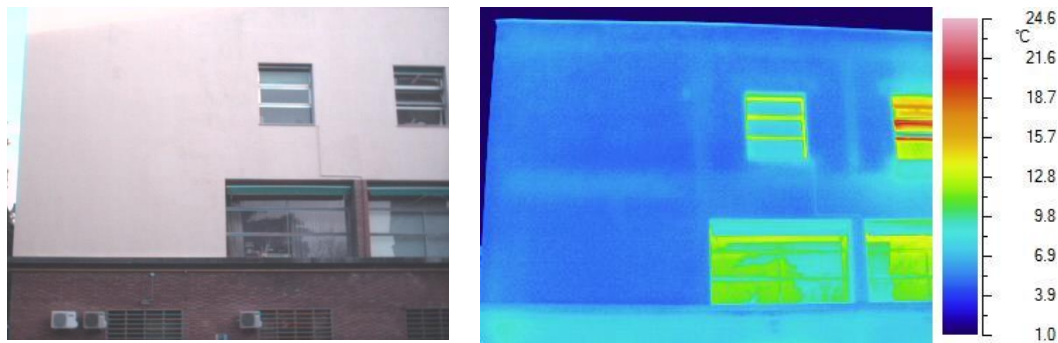


Figure 25 – Thermography of building 1. On the left: the façade, on the right: thermal bridges on the façade can be found (source: Garai et al., 2014)

Regarding the heat transfer coefficients of walls and windows (see 5.2.2). It was noted that 26% of the thermal transmittances of the opaque walls are between 1.00 and 1.20 W/m²K as Table 8 shows. The thermal transmittance of the walls is higher with respect to the typical values of historical buildings (see Table 1 in 2.1). It would be expected the walls to have values around 0,5 W/m²K due to their air gap of insulation. This situation shows that better insulation is required. Alike the opaque walls the thermal transmittance of the windows is higher than the

⁹ The figures referring to the energy use at both fortresses are dated 2012.

typical values of buildings (see Table 1 in 2.1). Most of the windows are original from 1935 consisting of single glazing with metal frame.

Table 8 - "U" value range of the walls at the Faculty of Engineering (source: Garai et al., 2014)

"U" value range, walls	%
$U. < 0,40$	0,0%
$0,40 < U \leq 0,60$	9,3%
$0,60 < U \leq 0,80$	4,7%
$0,80 < U \leq 1,00$	4,7%
$1,00 < U \leq 1,20$	25.6%
$1,20 < U \leq 1,40$	16.3%
$1,40 < U \leq 1,60$	11.6%
$1,60 < U \leq 1,80$	9.3%
$1,80 < U \leq 2,00$	7.0%
$2,00 < U \leq 2,20$	4.7%
$2,20 < U \leq 2,40$	2.3%
$2,40 < U \leq 2,60$	2.3%
$U > 2,60$	2.3%

Table 9 shows that 44% of all windows present a "U" value between the range of 5.5 and 6.0 a W/m^2K . However it is possible to find windows with double glazing. The measured thicknesses of double glazing are 4/8/4 (8 mm air gap) and the thermal transmittance value of the entire window is $3.14 W/m^2K$. Both thermal transmittances of single and double glazed windows are higher in comparison to typical values. Again, these values show that windows require better insulation.

Table 9 - "U" values range of the windows at the Faculty of Engineering (source: Garai et al., 2014)

"U" value range, windows	%
$U \leq 3.0$	1.2%
$3.0 < U \leq 3.5$	9.4%
$3.5 < U \leq 4.0$	1.2%
$4.0 < U \leq 4.5$	3.5%
$4.5 < U \leq 5.0$	30.6%
$5.0 < U \leq 5.5$	10.6%
$5.5 < U \leq 6.0$	43.5%
$U > 6.0$	0.0%

The building exhibits singular and historical characteristics that over the years have discouraged the replacement of building envelop elements. The architectural constraints that forbid working freely on the opaque and transparent surfaces are:

- External opaque surface: terranova plaster. Some external opaque surfaces are finished with a plaster named terranova of about 10 cm thickness that is forbidden to remove.

- External opaque surface: exposed bricks. Some external opaque surfaces are finished with exposed bricks that could not be covered.
- External transparent surface: iron windows. The larger part of windows is from Curtisa, a type of iron with historical value.
- Floors. In this building they used experimental floor for the period that preserve an historical value.
- Perret underfloor. Underfloor historical acoustic system named Perret was installed at the ceiling of the floor and must be preserved.
- Internal surfaces. Some internal surfaces could not be removed or covered such as the marble ones.

Regardless of the constraints, there are always liable solutions to applicate to improve energy performance of heritage buildings. The joint research and work of various experts allow organisational barriers to be overcome proposing solutions on the topic of building envelope, electrical appliances and heating systems and organisational measures.

5.3.3 Industrial heritage in Budapest (Hungary)

The current “Meter House” purpose is storage, using no energy. Alexa et al. (2014) resorted to a feasibility study previously performed. The study used assumptions of the expected functioning to estimate an energy profile of the “Meter House”. The “U” values presented are based on the average “U” values of the type of building materials used in meter house. Therefore, actual information regarding the thermal performance of the building is not available.

5.3.4 Comparison

As written in 5.2.4, an energy audit for heritage buildings should focus on the three topics: i) building envelope; ii) electrical appliances and heating systems; and iii) organisational measures. Therefore, Table 10 shows the results of the energy audits carried out divided into those three topics.

On the topic of building envelope, walls and windows are comparable. All the walls of the buildings under study are insulated except for Fort de Gagel and the guardhouse at Fort aan the Klop. Analysing the “U” values of the walls, the insulated wooden walls of the barracks at Fort aan de Klop show lower thermal transmittance than the typical values of heritage buildings. Here, the insulation was effective and should be considered as an example of good retrofitting for heritage buildings. The “U” values of the windows are higher than the typical values. Nevertheless, the calculated “U” values of the fortresses and the Faculty of Engineering are approximately the same. Hence, all buildings should consider the retrofitting of windows. The main reason for these values to be higher than the typical ones is the preservation of original building envelope elements. The constraints forbid working freely on refurbishing and/or retrofitting the surfaces.

On the topic of electrical appliances and heating systems, M. Bonnike provided energy use values. The energy use values of both fortresses showed the appliances/operations that consume more energy. The next section will discuss possibilities for reducing those values.

The topic of organisational measures refers to human behaviour but also to energy use management and maintenance of heritage buildings. Garai et al. (2014) presented the constraints imposed at the Faculty of Engineering by architectural preservation when refurbishment and/or retrofitting processes are foreseen. These constraints are included as organisational measures due to the fact of being organisational/political impositions to the retrofitting. Regarding the other two buildings no information was available on this topic.

Table 10 – “Analysis” phase comparison

	Fort Gagel, Utrecht, The Netherlands	Fort aan de Klop, Utrecht, The Netherlands	Faculty of Engineering, Bologna, Italy	The “Meter House”, Budapest, Hungary
Building envelope	<ul style="list-style-type: none"> - Single glazing: 5.7 W/m²K. - Double glazing: 3.3 W/m²K. - Walls (barracks): 1.16 W/m²K. - Roofs (barracks): 2.08 W/m²K. - Floor: 0.47 W/m²K. 	<ul style="list-style-type: none"> - Single glazing: 5.7 W/m²K. - Double glazing: 3.3 W/m²K. - Walls (barracks): 0.82 W/m²K. - Roofs (barracks): 1.08 W/m²K. - Floor: 0.47 W/m²K. 	<ul style="list-style-type: none"> - 26% of all the thermal transmittances of walls are between 1.00 and 1.20 W/m²K. - Single pane transmittance: 5.75 W/m²K. - 14% is of double glazing. Thicknesses are 4/8/4 (8 mm air gap) and the thermal transmittance is 3.14 W/m²K. 	
Electrical appliances and heating systems	<ul style="list-style-type: none"> - Heating and lighting reflect the highest electricity uses. 	<ul style="list-style-type: none"> - Kitchen and cooling equipment are the major parts using electricity. 		
Organisational measures			<ul style="list-style-type: none"> - Architectural constraints have discouraged the replacement of the windows and frames. 	

5.4 Improve phase

As discussed in section 4.2, this phase presents the available solutions that might be considered in order to improve the energy performance regarding the building envelope and the electrical appliances and heating systems. It also studies how organisational measures can help to make historical buildings more energy efficient while preserving their heritage value. This section shows possible solutions towards a sustainable and energy efficient retrofitting. This was done having as a starting point both the energy data that has been collected for each building (see 5.2) and their actual energy performance (see 5.3). As in the previous sections, this chapter discusses first the suggestion for improvement in each case and it finalizes with a comparison.

5.4.1 Historic fortresses in Utrecht (Netherlands)

At the moment of writing the present thesis no information related to the Fort de Gagel was available related to “improve” phase. An exercise of possible improvements for Fort de Gagel is complex: everything could be applied because there are unknown parameters for the future expansion and use. In contrast, three scenarios with measures to improve energy efficiency were proposed for Fort aan de Klop. The different scenarios start with the current situation and then go from less ambitious to more ambitious scenarios. The less ambitious scenario is “Scenario C” as a first step in energy reduction. It proposes measures of the report by Janssen (2012). These measures refer to insulation, energy generation from solar panels, lighting and smart energy reduction such as replacement of old freezers and refrigerators for one big cooling device. “Scenario B” refers to water and surroundings smart use, heating systems and ventilation in addition to what was referred in “scenario C”. “Scenario A” includes some of the previous measures. This scenario aims for autonomy. Some of the measures proposed in scenario A are (to see the complete list refer to **Appendix 2: How to draw an energy profile without resorting to an auditing company?**):

- Placement of insulated glass in the guardhouse. HR++ glass is not permitted because of the monumental status. Nevertheless, secondary glazing could be a possibility. This solution is in line with the findings reported in section 3.6.1.
- Use of a motion sensor for lighting. A motion sensor can be the solution for needless lighting that should be turned off such as hallway lighting in fortresses that are on all day.
- In addition LED technology should be used. LED lighting is a solution mentioned in as a best practice (see 3.6.3). It uses less energy compared to halogen and low energy light bulbs currently in use. Khan & Abas (2010) stated that 23 W compact fluorescent lamps (CFL) or 15 W LED lamps emit the same quantity of luminous flux as a standard 100 W incandescent lamps.
- Placement of solar panels to supply renewable energy. To cover the rest of energy demand, place a windmill of 15 metres high. The amount of energy that it is expected to be delivered with these RES was unavailable at the moment of writing this report. Nevertheless, these two solutions show that RES integration is viable and a way to use the land surrounding the fortress otherwise unusable. This solution preserves the architectural design and historical value of the fortress.

- Option 1 for heating: Biomass stove + solar boiler + energy recovery from shower water. The suggestion is to install 2 biomass stoves in combination with a buffer tank. And to connect the solar boiler system to the buffer tank. There are 12 showers in the barracks that would provide water to be filter and reused. The combination of the three systems is expected to cost $16200+2500+14400= 33100\text{€}$.
- Option 2 for heating: Vertical heat exchanger being soil the source. The advantages of vertical ground heat exchangers are that they require smaller plots of land areas and can yield the most efficient ground source heat pump system performance (Zeng et al., 2003). This system is environment-friendly, causing less carbon dioxide emission than conventional alternatives.
- Place an energy manager system. This is a smart and innovative measure to monitor energy consumes. This goes in line with smart monitors discussed in 3.6.3.
- Replacement of separate old freezers and refrigerators for one big cooling device. Cooling is one of the activities consuming large amounts of energy at Fort aan de Klop, (see 3.5.1). This new equipment should be energy labelled as mentioned in 3.6.3.
- At the moment there is no mechanical ventilation except for the sanitary rooms. The need of mechanical ventilation is uncertain. As mentioned in section 2.1, the ability to breath of heritage buildings minimizes the requirement of mechanical ventilation. However this uncertainty depends on the conditions and purposes of the building. By the end of the feasibility study, M. Bonnike (personal communication, October, 2014) will be certain about this topic.

The proposed measures to improve the energy performance of the Fort aan de Klop are ambitious. However, since part of the Fort was renovated in 2005-2007, the measures suggested are in line with the replacement of what already existed and was inefficient. These measures cover the best practices discussed in chapter 3, namely: insulation, heating systems, lighting and RES integration. The correct implementation of these improvements will increase the energy performance of the overall building. Additionally to energy conservation, some other measures could be of use to help the owners of this Fort in the endeavour of having a sustainable building. These additional measures proposed are described as follows:

- Reuse of water with the purification system helophyte filter¹⁰. In situ purification is used to pre-purify rainwater and grey water prior to it being dumped in the sewage of the neighbourhood (Vogtländer & Henfriks, 2004). Water purified through this system could be used for the toilet.
- Waste separation system and reuse of compostable waste for the green surroundings. The compost can replace soil conditioners supporting humus formation, which is a benefit that cannot be achieved artificially (Hermann et al., 2011).
- A small greenhouse for growing herbs and vegetables for the restaurant in combination with an aquaponics system¹¹. This is a sustainable measure promoting a closed loop: fish are fed with waste of the kitchen producing hummus that will fertilize plants. It can be associated to an organizational measure since the idea is a twofold

¹⁰ The helophyte filter serves to remove the organic nutrients nitrogen and phosphates from the water (D'Ersu, 2005)

¹¹ Aquaponics is the combination of cultivation of plants and aquatic animals in a balanced recirculating environment. In aquaponics system, the nutrient-rich water that results from raising fish provides a source of natural fertilizer for the growing plants. As the plants consume the nutrients, they help to purify the water that the fish live in (Conte & Thompson, 2012).

responsibility: responsible entity for the fortress but also people working in the restaurant.

5.4.2 Historic public buildings/ iconic buildings in Bologna (Italy)

Garai et al. (2014) suggested potential measures to improve the building envelope.

- 1) Blown-in cellulose insulation in the air layer of walls. Cellulose has low thermal conductivity and is used to reduce building heat loss and to reduce noise transmission. This measure allows 6% energy savings according to the model used and calculations performed by Garai et al. (2014).
- 2) External thermal insulation (on walls without architectural constraints). This measure allows 2% of energy savings. A rendered system is suggested as one of the most widely adopted solutions of external insulation (see 3.6.2). In this system, insulation is fixed mechanically or with an adhesive to the existing wall and a reinforced render finish is applied directly to the insulation. External insulation protects the fabric of the building, improves airtightness and is of easy installation (Roberts, 2008).
- 3) Replacement of windows without architectural constraints. This measure allows 1% of energy savings. It is suggested that the existing windows be replaced by the innovative solution “smartwin” discussed in 3.6.1. This window system gives the possibility to combine the historical details of the window and achieve comfort standards of a modern window.
- 4) Roof thermal insulation. A better thermal insulation of the roof leads to an increased living comfort and contributes to the energy balance of the entire building. However, in this case insulating the roof allows only 1% of energy savings. This might be because the roof is already a good barrier without thermal bridges.
- 5) Replacement of central heating boiler with new condensing boiler. This measure allows 23% of energy savings. A condensing boiler achieves efficiencies typically higher than 90% using waste heat to pre-heat cold water entering the boiler. The use of condensing boilers is obligatory or encouraged with financial incentives in many countries, for example in the UK (Energy Saving Trust, 2005).
- 6) Zone control with thermostatic radiator valves. This measure allows 13% of energy savings. Sensors and thermostats are technologies that optimize the operation of the regulation and monitoring systems in order to reduce energy consumption of buildings (Pfluger et al., 2013).

The heating distribution system consists of non-insulated pipes placed in the walls resulting in loss of heat along the pipelines going towards the radiators. Additionally, it is suggested the insulation of the heating distribution pipelines. Insulation is one of the practices that are generally taken as a first step in energy efficiency in buildings but usually thought regarding windows, walls and roof (see 3.6.2). Fiberglass is widely used to insulate pipelines.

These are the measures that can be applied at the Faculty of Engineering despite the constraints forbidding a free refurbishment intervention (see 5.3.2). This case study shows us that it is possible to overcome those constraints and find solutions necessary to improve energy performance considering the protective value of the building. It shows how a multidisciplinary team can elaborate a list of refurbishment works required on the basis of the building audit, his

experience and the available budget (Flourentzou & Roulet, 2002). A thorough analysis and a constructivist approach will help an expert in designing retrofit scenarios/options. There are several criteria under each of the three key topics to improve energy performance (Figure 10, section 3.5.1). Using this layout, it is possible to evaluate the different criteria that can contribute to a poor energy performance among the building envelope, the electrical appliances and heating systems and the organisational measures. Whenever one of these criteria (or part of one) is unchangeable, the designers of the retrofitting have to focus on other criteria to maximize energy performance improvement.

5.4.3 Industrial heritage in Budapest (Hungary)

Reconstruction and modernization of historic buildings always conflicts with the fundamental value-perception problem which exalts the shell of these monuments. In the case of Hungary the rigid preserving of the facades and roof-forms undermines all visible interventions. No outer isolation on walls, no photovoltaic cells on roof, no insulated new windows at the facades are allowed. The Meter House also has to maintain its protected industrial character so implementation of outside interventions is unmanageable.

Regarding the building envelope and energy consuming systems inside the industrial building in Budapest, Alexa et al. (2014) presented some suggestions on how to refurbish and retrofit the “Meter House” were proposed:

- 1) The glazing shall be equipped with heat resistant coating. This measure applies to the windows that cannot be replaced.
- 2) A solution to avoid moisture accumulation and structural damage is using additional thermal insulating glass. Tightly sealed new windows reduce the exchange of air that had been adequate in the past thus increasing the moisture content of the interior air (Roberts, 2008). For that reason additional thermal insulating is suggested.
- 3) Addition of curtain wall windows with undivided glazing attached to the restructured inner surface of the walls will preserve the original divisions of the windows. A curtain wall is a non-structural covering of a building allowing natural light penetration and thermal comfort.
- 4) To thermal insulate the building, internal insulation system (YTONG Multipor™¹²) arises as a solution since external insulation is prohibited on listed buildings in Hungary. After calculating the heat transfer of the insulated walls and the vapour transfer calculation, it is suggested to install a 100 mm thick layer of insulation on the inner surface of the wall. In this case the thickness of the insulation depends on the result of the vapour transfer calculation. The installation of insulation in the building envelope will result in improved heat transfer coefficients as Table 11 shows.

Table 11 - Insulation of the building envelope (source: Alexa et al., 2014)

Element	U _{existing}	U _{expected}	Solution
External wall	1.18	0,38	Internal themal insulation
Window	6.5	2.0	Internal thermoglass
Roof	2.21	0.1	Thermal insulation

¹² YTONG Multipor™ is a thermal insulating board made of mineral material (source: DIBt, 2014).

It is possible to notice that the existing “U” values are improved after thermal insulation placement.

- 5) Heat recovery from wastewater and HVAC systems. With appropriate technology, wastewater heat that otherwise would end up as waste in the sewage system can be utilized. According to Alexa et al., (2014) available HVAC options were investigated with the conclusion that the HVAC systems selected were those that require the least visible mechanical and architectural elements (e.g. chimneys).

On the topic of energy systems, it is planned that gas will not be used after refurbishment and implementation of previous measures. If the “Meter House” functions as Contemporary Cultural and Communication Centre, then heat recovery from wastewater is a cheap energy source available in urban areas and production facilities. Figure 26 shows the envisioned wastewater heat recovery system. The system works by extracting the heat from the shower or bath water sent down the sewer. The temperature of communal wastewater falls in the range between 10°C and 20°C, while industrial wastewater can be warmer than that. Therefore, the wastewater is stored in closed pipe loops buried in the ground. The wastewater heats the circulating fluid of the heating system in the heat exchanger. In the heat pump, through phase changes, the circulate fluid is heated/cooled depending on the thermal needs of the building. The heat from the wastewater is harnessed to underfloor heating or surface cooling. The location of the gasworks is also an advantage: wastewater collecting ducts are under the main road at a distance of hundred meters. Due to its virtually constant temperature, wastewater heat offers much better energy efficiency than soil heat or groundwater. Part of the cooling energy needs during the winter is covered by free cooling. Free cooling is the method of storing outdoors coolness during the night, and supply to indoor air during the day. Main advantages are cooling with reduction of greenhouse gases and indoor air quality maintenance inside the building (Raj & Velraj, 2010). The other part of the cooling energy is provided by heat recovery by high temperature of exhausted air (efficiency higher than 80%). Therefore, the energy need of the HVAC system would be reduced due to the architectural design and the heat recovery.

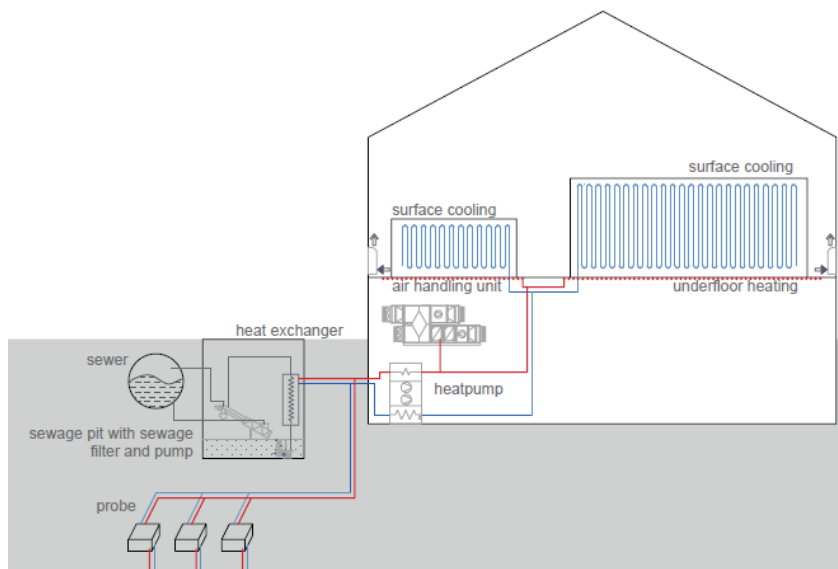


Figure 26 - The envisioned wastewater heat recovery system (source: Alexa et al., 2014)

The refurbished “Meter House” will use existing structures as an outer shell, providing the necessary insulation within it. The insulating structure will be built on the internal side thus the outer cladding and the layout of the openings will be preserved. The characteristic truss structure of the roof visible from the inside will be preserved during the refurbishment, so the required insulation has to be installed on top of it. In this way, the roof will become higher yet the inclination and roofing material will remain the same. Therefore, the outer appearance of the building will remain unaltered. The roof insulation is the biggest factor saving energy. Besides this, internal wall insulation will be installed on the facades, which may be only used at a minimal thickness even with advanced condensation control. This inner wall gives the framework of the internal insulated glass walls which has an invisible structure. This glazing helps the appropriate insulation of the outer layer behind the existing windows. The estimation is that the implementation of these measures results in energy savings of 96.29 MWh/annual compared to the use of the building before refurbishment.

5.4.4 Comparison

As done in the previous sections, to facilitate the proposition of measures focusing on improving energy performance of heritage buildings, the comparison is also divided in these topics: i) building envelope; ii) electrical appliances and heating systems; and iii) organisational measures as Table 12 shows.

Table 12 – “Improve” phase comparison

	Fort Gagel, Utrecht, The Netherlands	Fort aan de Klop, Utrecht, The Netherlands	Faculty of Engineering, Bologna, Italy	The “Meter House”, Budapest, Hungary
Building envelope		<ul style="list-style-type: none"> - Possibility of secondary glazing at the guardhouse. 	<ul style="list-style-type: none"> - Blown-in cellulose insulation in the air layer of walls. - External thermal insulation (on walls without architectural constraints). - Replacement of windows without architectural constraints. - Roof thermal insulation. 	<ul style="list-style-type: none"> - Additional thermal insulating glass. - 100 mm thick layer of insulation (YTONG Multipor) on the inner surface of the wall. - Curtain wall windows with undivided glazing attached to the restructured inner surface of the walls. - Glazing with heat resistant coating.
Electrical appliances and heating systems		<ul style="list-style-type: none"> - Placement of solar panels and a windmill of 15 metres high. - Vertical heat exchanger (source is the soil). - Use LED lighting. 	<ul style="list-style-type: none"> - Replacement of central heating boiler with new condensing boiler potential measures: central heating. - Zone control with thermostatic radiator valves. 	<ul style="list-style-type: none"> - HVAC systems that require the least visible mechanical and architectural (chimneys etc.) elements. - The heat recovery from waste water is a cheap energy source continuously available in urban areas and production facilities.
Organisational measures		<ul style="list-style-type: none"> - Reuse of waste water. - Waste separation system and reuse of compostable waste for green surroundings. 		<ul style="list-style-type: none"> - Implementation of outside interventions is unmanageable.

Regarding the building envelope, solutions were suggested for windows, walls and roofs. It was noted that window insulation is a requirement transversal to all the case studies. The solution suggested for Fort aan de Klop is in line with the most widely adopted solution for window retrofitting, namely, secondary glazing (see 3.6.2). However, the replacement of windows could be done resorting to “smartwin historic”. A curtain wall windows works with the same purpose as secondary glazing on the inner surface. The thermal performance of cavity walls is normally improved by filling the cavity with insulation, which can reduce the heat loss through the walls by up to 40% (Roberts, 2008). Therefore, insulating walls is a priority aspect when retrofitting heritage buildings. Filling the cavity with insulation is the suggested solution at the Faculty of Engineering. At the “Meter House” internal insulation is proposed involving lining the inside faces of the wall with plasterboard on a frame. These are two solutions that will improve the energy and thermal performance of the building. At Fort aan de Klop, at some areas the walls were already insulated so there is no information about predicted plans on more insulation. Regarding roof retrofitting, insulation was a shared solution for the Faculty of Engineering and the “Meter House”. There are different methods to insulate roofs depending on if they are pitched or flat (see 3.6.2). In the case of the flat roof in Italy, the installation of thermal insulation on the roof allows 1% of energy savings. In the case of the pitched roof in Hungary, roof insulation is the biggest saving energy factor. In the case of the Netherlands, there is no consideration regarding the insulation of roofs. The reason for that may be the fact that Fort de Gagel is covered by earth and vegetation and Fort aan de Klop presents an “U” value lower than the typical value of heritage buildings. Extensive retrofits include upgrading windows, external and internal insulation and insulation applied to ground floors. Such retrofitting reduces wall and roof heat losses by a factor of 50–80% (Roberts, 2008).

Regarding the topic of electrical appliances, M. Bonnike (personal communication, October, 2014) suggested that all the energy generated has to be renewable (sun and wind). Within Fort aan de Klop, RES integration is feasible in agreement to what is written in 3.6.3. These two solutions can be applicable because the historical value of the building is preserved and there is a way of using land surrounding the fortress otherwise unusable. Garai et al. (2014) suggested the replacement of central heating boiler with a new condensing boiler as it is written in literature (see 3.6.3). Alexa et al. (2014) provided no information regarding the production of electricity. Regarding the heating of the building, a vertical heat exchanger using soil as source emerged as a solution according to Bonnike (personal communication, October, 2014). In contrast, Alexa et al. (2014) assumed that heating is provided by heat recovery from wastewater. This is another solution to produce heating without using fossil fuels. The three case studies show that it is possible to use RES in heritage buildings.

Energy efficiency improvements based on organisational measures were unavailable at the moment of writing this report (see 5.2.4). Organisational measures can be applied in every building to make people aware of a rational use of energy and resources. The Rijksmuseum in the Netherlands stands as an example where organisational measures were implemented aiming at increasing energy efficiency. At the Museum, when there are no visitors in a room the lighting is switched off and the air is recirculated to keep the climate at a constant temperature and humidity level. An interesting aspect worth mentioning is the fact that both Fort aan de Klop and the “Meter House” envision the cleaning and reuse of water. This reflects the awareness raised by the responsible entities towards a rational use of water.

5.5 Control phase

This is the last phase of the DMAIC approach. It discusses how to monitor the measures suggested in “improve” phase. Insights are offered on how the energy efficient improvements should be maintained and verified in the long term.

The refurbishment project should be carried out by a multidisciplinary team having the same mission within the project. Inside the project, someone expert has to be responsible for conducting the energy audit and/or to conduct the monitoring phase. The three case studies provided no information regarding the monitoring phase. This indicates that they are missing the last step when retrofitting and/or refurbishing heritage buildings. As explained in 3.6.5, the follow-up plan is imperative for the preservation and maintenance of good conditions. Without a monitoring plan, it is not possible to verify the effectiveness of the implementation of the technologies and best practices suggested in 5.4. Therefore, it is suggested a number of measures that can be applied to monitor the improvements suggested. These measures are under the topics of i) building envelope, ii) electrical appliances and heating systems and iii) organisational measures as follows:

- Building envelope
 - Control temperatures and relative humidity (RH) inside the building with thermostats and humidistat, respectively. For the conservation of important museum collections in historical properties, controlling RH is an essential factor. Information was that there was no temperature control. Therefore, the utilisation of thermostats and humidistats avoids deliberate fluctuations of temperature and RH in the valuable historic interior and thereby limits the risk of any damage. Electric radiators can be automatically switched on/off if connected to the thermostats saving unnecessary heating/cooling energy. (Saïd et al., 1997; Neuhaus & Schellen, 2007). This advice is for the three buildings under study but also applicable to any kind of historical building without temperature and RH control. If it is possible to set and maintain a temperature inside of a building, then the insulation of windows, doors and/or roofs was effective.
 - Perform another thermography (after execution of refurbishment works). This advice is specific to the Faculty of Engineering since it was the only building which performed an in situ energy audit. A new evaluation of the energy performance through new thermography would show if the thermal bridges revealed on the previous one performed were eliminated or, at least, diminished.
 - It is advised the other case studies and any kind of historical buildings to perform an energy audit after refurbishment processes. As discussed in “measure” phase, it was noticed that the best techniques to evaluate energy performance such as air tightness, thermography, heat flux and co-heating were disregarded in Dutch and Hungarian case studies (see 3.5.2). Once again, it is referred the layout of an energy audit developed for heritage building (see 3.5.1 and Appendix 2: How to draw an energy profile without resorting to an auditing company?). The energy audit has to be performed if the owners/responsible entities want to know the energy profile and the thermal conditions of the building. Since no energy audits were performed at both

fortresses and at the “Meter House”, it is suggested that one should be executed after the refurbishment. A blower door test and/or a thermography should be performed. The blower door test would inform about the heat losses through air infiltrations and a thermography would localize the thermal bridges and check where the materials change or are irregular.

- Measure and/or recalculate “U” values after placing insulation and compare estimated “U” values (theoretical) with real “U” values. These analyses will also show if the solution implemented either replacement of windows or addition of layer of insulation were successful. This can be included as a part of the energy audit.
- Electrical appliances and heating systems
 - The owners/responsible entities of the buildings should analyse and compare energy bills before and after implementation of the measures suggested in 5.4. The most important aspects to look at in the energy bill are: i) the billing period (the supply period); ii) whether the bill is based on an actual reading or an estimate; iii) the number of days the bill covers; iv) the total amount of electricity/gas used; v) the prices paid per kWh/m³ in different periods, i.e. peak and off peak rate, and for the total billing period. Afterwards it will allow better knowledge of the energy profile of the building. It is suggested that users build a chart where one can read the energy consumed during one year. By drawing two lines, one prior the refurbishment process and other posterior the refurbishment process, the users will observe the differences in consumption in the previous and subsequent years. The time interval should be similar, that is to say, the annual billing period has to be coincident in both years under study. Figure 27 shows an example of an energy profile of the cooling energy need before and after a refurbishment process. It is possible to observe that the cooling energy need after renovation is reduced compared to the energy need of the original building.

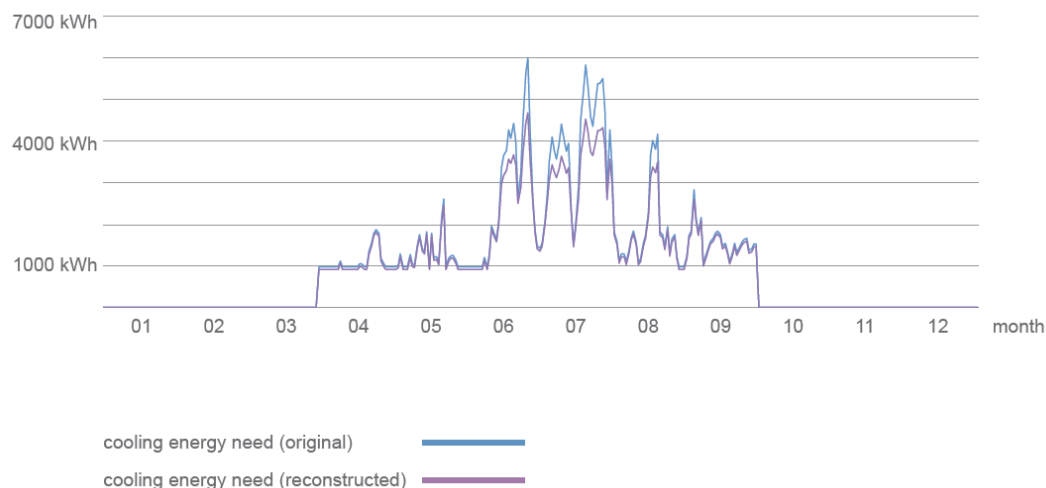


Figure 27 - Example of an energy profile (source: Alexa et al., 2014)

- If at some point, users notice an anomaly in energy use values there are two things to suggest. First to draw energy profile based on the energy use in the building (see Appendix 2: How to draw an energy profile without resorting to

- an auditing company?). If the users are unable to identify and rectify the problem they should ask to expert companies for a professional energy audit.
- The multidisciplinary team responsible for the refurbishment of the building should meet regularly (every year) to discuss if any anomaly has been identified. In this way knowledge can be sustained.
- The energy use during the night is another factor requiring monitoring. Some appliances such as computers and lighting are constantly turned on in heritage buildings. The occupants responsible for the buildings should be advised and reminded to turn off all the appliances that should not operate during the night before closing the buildings.
- The installation of smart monitoring as suggested for Fort aan de Klop is a feature that controls energy use values in real time (M. Bonnike, personal communication, October, 2014). The Company Navetas developed in 2012 a technology that – in addition to tracking the overall energy use – is able to distinguish the various power loads from one another (i.e. refrigerator, television, washing machine, etc.). Smart meters act as a two-way interface with the costumer's own appliances transmitting data, receiving commands, monitoring supply and communicating with appliances.
- Organisational measures
 - In 3.6.6 it was presented the rules of thumb on organisational measures in heritage building to take into account when it comes to the implementation of refurbishment and/or retrofitting solutions. Hereby it is presented the rules of thumb after the implementation. Human behaviour plays a key role in unlocking additional sources of energy savings while ensuring the persistence of these savings into the future. Energy savings achieved through technical energy efficiency improvements can be cancelled out by inappropriate human behaviour (IEA, 2014). It is estimated that energy and greenhouse gas savings related to behaviour is in the range of 20% to 30% over the course of the next five to ten years (IEA, 2014).
 - When users are informed about appliance efficiency labels, consumers adopt the most efficient technology and this is particularly true when there is an explicit link between energy efficiency savings and monetary savings (IEA, 2014). This information should be contained on the advertising/explanatory leaflets of the specific heritage building.
 - The visitors/occupants of heritage buildings should be able to read information about the energy performance and retrofitting interventions at the sites (in the fortresses, in the Faculty of Engineering, in the “Meter House” and in all heritage buildings). The work involved in refurbishing historic buildings should be disclosed so visitors/occupants gain awareness of the relevance regarding maintenance and improved energy performance in these heritage properties.

Energy consumption is affected by the physical characteristic of the building, the available budget, functioning of the building but also by the behaviour of the occupants. Controlling the implemented measures is a difficult task. It requires availability and will from people attending the buildings, to maintain better energy performances and energy autonomy in some cases. People operate energy efficient solutions when they are aware of the repercussions of its operations (IEA, 2014). The occupants of the buildings need to feel responsible for the management of their installation. Therefore, in order to assure that the implemented energy

saving retrofitting measures are effective it is essential to inform the users about the functioning of new appliances, the retrofitting options implemented and how to maximize the energy performance. This chapter discussed the case studies and performed the possible comparisons with the data gathered from each party of ReFoMo project. Conclusions are drawn in the following chapter of this report.

6 Discussion

Chapter 2 discussed the characteristics of heritage buildings and chapter 3 described the widely adopted solutions when these buildings require refurbishment and retrofitting processes to improve their energy performance. The main research question that led this research was: “How to improve energy performance of heritage buildings?”. This question was answered by literature study and by a comparative analysis on the three cases studies. Chapter 5 presented the results of the comparative analysis.

The present chapter discusses the findings of this research, namely the suggestions in order to perform an energy efficient retrofitting for heritage buildings. In section 6.1, the idea of a multidisciplinary team to be responsible for the whole project is presented. In section 6.2, the energy audit for heritage buildings was elaborated. The final section of this chapter gives an overview of the best practices of techniques and retrofitting solutions discussed along the report. Figure 28 shows the guidelines to refurbish and/or retrofit heritage buildings.

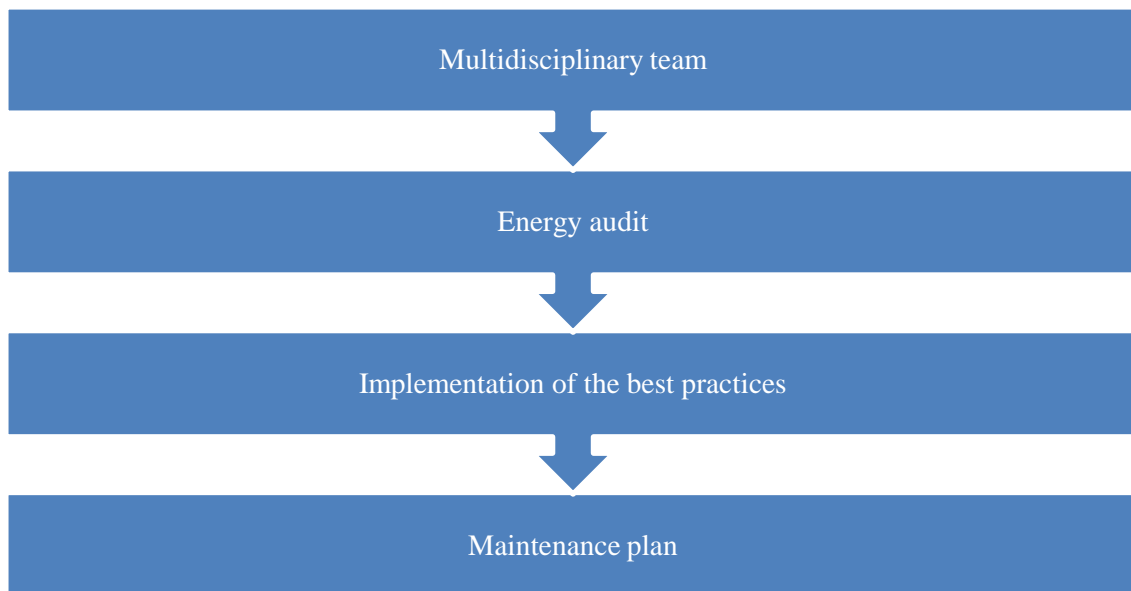


Figure 28 - Guidelines for refurbishment and/or retrofitting of heritage buildings

6.1 Multidisciplinary team

The idea of creating a multidisciplinary team for refurbishment and/or retrofitting processes has been a constant finding through this research (sections 3.1, 3.2.13.2.1, 3.6.2, 3.6.4, 3.6.6 and 4.2). The creation of a multidisciplinary team is essential during the refurbishment interventions of heritage buildings. This team should comprise architects, civil engineers, historians, energy experts, politicians, civil servants, financial institutions, owners, users, companies of specialized energy auditing and communication professionals that will provide the most complete data gathering. The goal of multidisciplinary is the contribution of each discipline to both understand the heritage value of the building and the renovation that the building needs to undergo.

The multidisciplinary team have as responsibilities:

- i. Design the energy audit;
- ii. Supervise/conduct the energy audit (i.e. energy auditing expert);
- iii. Present the results in a report that shows relevant information for each of the team members;
- iv. Meet every year to monitor the benefits of the “improve” phase.

At the beginning of ReFoMo project there were several identities recognised as partners, namely: Province of Utrecht, ARCADIS Netherlands BV, Utrecht University, NEGOS, Centre for Applied Research on Buildings and Construction (CIRI-EC) and AIDICO. It is expected that these companies have experts in the fields of architects, civil engineers, energy, policy making. The structure of the team resembled the typical functioning of the building sector, namely, a segmented team. However, it is possible to state that the work was not carried out properly since there was no energy audit carried in two of the three case studies within the project. The multidisciplinary team created for the whole project should have been created for each case study.

6.2 Energy Audit

The different parties concerned with the energy efficiency of heritage buildings should perform an energy audit. This audit is compulsory as the first step of the retrofitting process. The significance of an energy audit lies in the possibility to identify the sources of over consumption and where it is possible to implement energy saving measures. There are three key topics where energy savings can be implemented in heritage buildings: building envelope; electrical appliances and heating systems and organisational measures. Building envelope is defined as the part of a building that forms the primary thermal barrier between interior and exterior. Electrical appliances and heating systems refer to equipment consuming energy inside the building. The third key topic refers to organisational measures dealing with behaviour/political changes. These three topics are all of same importance.

An energy audit should have 4 different steps consisting of:

1. **Data analysis** of the building characteristics and energy use values to study the history of the building.
 - a) On the topic of building envelope, to understand which the ancient and modern parts are, the auditors should analyse the construction elements such as walls, floors and roofs.
 - b) On the topic of electrical appliances and heating systems the auditors should collect available data about energy systems and energy use pattern of the building.
 - c) On the topic of organizational measures the auditors should investigate if there are any constraints forbidding refurbishment processes.
2. **On-site survey** where a visual inspection of the building takes place elucidating about previous refurbishment interventions and about the working systems.
 - a) The auditors should use best available diagnostic and monitoring tools to evaluate energy performance of the building envelope. These techniques are: air tightness, thermography, heat flux and co-heating.
 - b) In parallel the auditors get engineering data of the building measuring luminance levels, heating and cooling systems and plug loads.

- c) At organisational measures level, the auditors should investigate the lighting, appliances or natural lighting use through surveys, observation or smart monitoring (smart meters).
- 3. **Evaluation of energy conservation opportunities** based on the energy use pattern of the building. The auditors should aim at analysing the energy needed and the energy actually used in order to improve the energy performance of the building.
 - a) The results of the techniques to evaluate the energy performance of the building envelope and the data gathered in step two are analysed.
 - b) The energy use values of the energy-consuming systems inside the building are analysed and evaluated.
 - c) The organisational measures implemented (if any) are recognised and its future application is evaluated.
- 4. **Recommendations** of energy savings to be implemented to improve the energy performance of the building under study. By the end of this process it is possible to present recommendations covering the three topics of interest such as:
 - a) insulating the building envelope;
 - b) replacing lighting system or a boiler;
 - c) proposing maintenance and energy management plans.

In section 3.5.1 it was delivered the layout of an energy audit specific to heritage buildings. Table 13 explains how the energy audit should be fulfilled based on the data gathered in both literature and case studies. The table shows the knowledge gained throughout this research: the four steps of an energy audit under each one of the defined three key topics

Table 13 - Energy audit for heritage buildings

	Building Envelope	Electrical appliances and heating systems	Organisational measures
1) Data analysis	<ul style="list-style-type: none"> - Characteristics of the building envelope (walls, floors, roofs). - Energy bills. 	<ul style="list-style-type: none"> - Available data about energy systems and energy use pattern of the building. 	<ul style="list-style-type: none"> - The architectural/design constraints that a building is subjected to. - Additional information.
2) On-site survey	<ul style="list-style-type: none"> - Air tightness test. - Thermography. - Heat flux test. - Co-heating test. 	<ul style="list-style-type: none"> - Luminance levels measurement. - Measurement of heating and cooling systems energy use. - Metering plug loads. 	<ul style="list-style-type: none"> - The use of lights, appliances or natural lighting can be monitored by surveys, observation or smart monitoring (smart meters).
3) Evaluation of energy conservation opportunities	<ul style="list-style-type: none"> - Analysis of the results of the test(s) carried out: air leakages, thermal bridges, “U” values and heat losses. 	<ul style="list-style-type: none"> - Reading and analysis of energy profile finding the energy conservation opportunities. 	<ul style="list-style-type: none"> - Reuse of waste water. - Waste separation system and reuse of compostable waste for green surroundings.
4) Recommendations	<ul style="list-style-type: none"> - Blown-in cellulose insulation in the air layer of walls. - External thermal insulation on walls. - Replacement of windows. - Glazing with heat resistant coating. - Roof thermal insulation. 	<ul style="list-style-type: none"> - Placement of solar panels and 15 metres high windmill. - Vertical heat exchanger (source is the soil). - The heat recovery from waste water is a cheap energy source continuously available in urban areas and production facilities. - Zone control with thermostatic radiator valves. - Use of LED lighting. 	<ul style="list-style-type: none"> - Implementation of energy use monitoring tools, such as motion sensors. - Development of workshops, learning sessions about the refurbishment interventions in the buildings.

Analysing the case studies (see chapter 5) it was noticed that only the Italian case performed an energy audit. It was performed a thermography and described the system plant. Although the audit was incomplete, it offered recommendations for both building envelope and the heating

system. Nevertheless, it missed following the evaluation under the three topics suggested and consequently an accurate and detailed energy audit. Regarding the Dutch case studies it was suggested that in addition to the “U” values calculations at Fort de Gagel and Fort aan de Klop, either an air tightness measurement or a co-heating test should have been performed to acknowledge the permeability of the building fabric. An air tightness measurement would assess air permeability and location of air leakage paths. A co-heating test would measure heat losses resulting from both infiltration and thermal transmission through the building fabric. However, to perform a co-heating test the fortress would have to be unoccupied to eliminate human behaviour variables. Since Fort de Gagel functions as offices and Fort aan de Klop as a restaurant, it is possible to vacate both fortresses. With regard to the Hungarian case, at the “Meter House” it was suggested that either a thermography or a heat flux measurement could have been done. The data resulting from either technique would provide the thermal conditions of the building. The thermography would analyse where the heat losses occur while the heat flux measurement would derive an in situ “U” value for the building elements.

When performed correctly, the outcome of an energy audit is signalling of areas where energy efficiency can be improved. The goal of an energy audit for heritage buildings is that nothing is left to analyse and improve in the building. Therefore, an energy audit is performed correctly when, by the end, the auditors give recommendations for all the elements referred within the building envelop, electrical appliances and heating systems and organisational measures. Once the energy audit is done and the recommendations on how to refurbish and/or retrofit the building under study are presented, the refurbishment team is prepared to start planning the interventions.

6.3 The best practices on how to refurbish a heritage building

Gathering the multidisciplinary team is the first best practice when aiming at refurbishing a historic building. Performing an energy audit is the second. The team is responsible for planning the refurbishment process which contains the ideas described as best practices on organisational measures in heritage buildings (see 3.6.6). These are summarized as follows:

- Know the importance of the buildings and its inside treasures (fixtures, fittings or features);
- Gather data regarding relevant characteristics of the building under study, such as historical use, goal, energy use bills and occupation of the building is crucial to understand the way forward;
- Minimise the physical and visual impact of any work or new equipment refers to the need of keeping the architectural design as little as possible changed;
- Promote the littlest intervention into historic fabric such as frames, windows or adornments on the walls to prevent their damage;
- Analyse if the techniques previously proven to work on historical buildings are a secure decision or if new materials and systems should also be considered and implemented. The use of modern materials, if essential, needs to be based upon an informed analysis where the implications of their inclusion and the risk of problems are fully understood.

Having these topics well defined, the refurbishment team can proceed to the refurbishment plan. ReFoMo can benefit from the renovation that Fort aan de Klop was subjected to between 2005

and 2007 if they replicate what was done there. At Fort aan de Klop the insulated wooden walls of the barracks show lower thermal transmittance than the typical values of heritage buildings. Here, the insulation was effective and should be considered as an example of good retrofitting for heritage buildings. There was no information available about the type of insulation used. However, the best practices on how to refurbish the building envelope of heritage buildings suggest that they might have installed a non-rigid insulating material between timber studs or battens erected internally to the wall, with the new internal finish applied to the timber structure to control vapour and careful isolate from sources of dampness (English Heritage, 2012).

Table 14 summarizes the best practices on building envelope refurbishment of heritage buildings. These best practices include the most widely adopted solutions, the innovative solutions and the solutions proposed by the case studies for each criterion within electrical appliances and heating systems.

Table 14 - Best practices on building envelope refurbishment of heritage buildings

Building envelope	Windows Secondary glazing (widely adopted solution + Fort aan de Klop + The "Meter House"). "Smartwin historic" (innovative solution). Glazing with heat resistant coating (The "Meter House").
	Draught-proofing Heavy-duty materials are particularly advisable.
	Floors From below the suspended floor with wood-fibre, compressed hemp, sheep's wool. From above the floor suspended with semi-rigid batts, boards or loose fill cellulose. Replacing solid floors carpets with wooden floors or tile.
	Walls Interior insulation: blown-in cellulose insulation in the air layer of walls (Faculty of Engineering). Layer of insulation (YTONG Multipor™) on the inner surface of the wall (The "Meter House"). Vacuum insulation panels (innovative solution). External thermal insulation (Faculty of Engineering). Useful materials include hemp-lime composites, sheep's wool and mineral wool. Multi-foil insulation (innovative solution).
	Roofs A variety of materials can be used from mineral fibre to natural materials such as wool of sheep for pitched roofs. Soft fibre rolls or unformed loose-fill materials for flat roofs. Green roofs (innovative solution).
	Shading devices Single glass type window (southern regions) and casement type windows (northern regions).

Secondary glazing is the most widely adopted solution and the solution proposed to retrofit windows at Fort aan de Klop and the "Meter Hosue". This is the most protective value solution of historic windows. However, it is suggested that the refurbishment team should confirm the possibility of replacing the existing windows for "smartwin". This solution conserves the historic character of the building and achieves comfort standards of a modern window.

Concerning draught-proofing, heavy-duty materials are particularly advisable. None of the case studies considered this solution but it is suggested that ReFoMo can benefit from these materials to better insulate windows and doors. The case studies did not refer to retrofitting floors. That circumstance suggests the floors are in good conditions and/or well insulated. At walls retrofitting, more solutions appeared in addition to the widely adopted. It was noted that the Faculty of Engineering suggested both interior and exterior insulation. The innovative solutions were not considered to retrofit the walls of the case studies. VIPs are fragile compared with conventional construction materials and edge effects are significant, requiring careful design and fabrication. Multi-foil insulation is made up of multi-layered reflective films only a few micrometres thick. This solution could also be applied into the case studies which chose other possible solutions. Only the Italian case study suggested roof insulation. Since they did not present how to thermally insulate the roof it is suggested options depending on the inclination of the roof (pitched or flat). Relating to shading devices, no options were proposed for the case studies. At Fort de Gagel windows are set back from interior shutters and at Fort aan de Klop windows are set back 400 mm so the walls work as shading devices. At the time of the renovation between 2005 and 2007, exterior window shutters of historic design were installed. Thus, ReFoMo can benefit from this installation if they replicate what was done there. Since no more information was available, it is suggested single glass type window for southern regions and casement type windows for northern regions.

Table 15 resumes the best practices on electrical appliances and heating systems refurbishment of heritage buildings. These best practices include most widely adopted solutions, the innovative solutions and the solutions proposed by the case studies for each criterion within electrical appliances and heating systems.

Table 15 - Best practices on electrical appliances and heating systems refurbishment of heritage buildings

Electrical appliances and heating systems	Electrical appliances Energy labelled appliances.
	Heating systems Wet systems (widely adopted solution). Active overflow propotype (innovative solution). Vertical heat exchanger using the soil (Fort aan de Klop); heat recovery from waste water (The "Meter House").
	Boiler Condensing boiler (widely adopted solution + Faculty of Engineering)
	Lighting Led technology (widely adopted solution + Fort aan de Klop). Luminaire "wallwasher" (innovative solution).
	Passive heating and cooling Use of transparent surfaces to gain heat and wall to storage it.
	RES integration Integration of solar roofs - not visible from the streets. Solar panels and Windmill (Fort aan de Klop) - utilization of wasteland.

Fort de Gagel has appliances used in offices and Fort aan de Klop has appliances used in restaurants. There is no additional information about this topic so it was advised the responsible

entities of the building to note the energy label of equipment. On the topic of heating systems, the innovative system was not taken into consideration to retrofit the buildings under study. However, the active overflow prototype was installed in a heritage building and showed that it is an advantage compared to decentralised systems with two openings per room (in and outflow) to the outside (impacting on the building structure). Therefore it could also be applied in the case studies. These proposed vertical heat exchanger using the soil at Fort aan de Klop and heat recovery from waste water at the "Meter House". The solutions proposed for the case studies can be extrapolated for other cases if there is soil available to storage heat. The widely adopted solution to retrofit boilers is a condensing boiler. The only case study concerned with this element suggested in accordance to the widely adopted solution. At lighting level, the widely adopted solution was proposed for lighting retrofitting at Fort aan de Klop: led technology. The innovative solution, luminaire "wallwasher", provides on one hand optimized visual scenery and on the other hand it should slow down the deterioration process that any material undergoes. Therefore, "wallwasher" can be installed in the buildings under study if it is possible to replace the luminaires. The opportunities for passive heating and cooling were neglected by the case studies. Therefore it was recommended the use of transparent surfaces to gain heat so walls storage it as the best practice. Regarding RES integration, examples were found in literature of integration of solar roofs. This solution could also be applied on the flat roof of the Faculty of Engineering. At Fort aan de Klop it is recommended the installation of solar panels and a windmill to generate electricity. This RES integration is possible due to the existing wasteland nearby the fortress.

Table 16 - Best practices on organisational measures in heritage buildings shows the best practices on organisational measures. However, the ideas suggested for the Fort aan de Klop and others towards the improvement of energy performances of heritage buildings are presented. Our suggestions are twofold: change in human behaviour and use of energy efficient controls and equipment.

Table 16 - Best practices on organisational measures in heritage buildings

Organisational measures	Changing behaviour Reuse of waste water (Fort aan de Klop). Waste separation system and reuse of compostable waste for green surroundings (Fort aan de Klop). Inform users about appliance efficiency labels. Inform the visitors/occupants about the energy performance and retrofitting interventions at the sites.
	Using energy efficient controls and equipment Control temperatures and relative humidity (RH) inside the building with thermostats and humidistat, respectively. installation of smart monitoring.

During the implementation process, a monitoring plan must be followed. After the implementation of the control tools suggested in 5.5, the multidisciplinary team for the historic properties have to assure a maintenance plan in long term conditions. They should be responsible to assure:

- Scheduled or periodic inspections by the responsible authorities focusing on the building fabric and structural elements.

- A specific unit to carry out maintenance work should be included by the responsible organisations and entities of heritage buildings.
- Financial incentives given to the entities responsible to carry out maintenance works in heritage buildings should be more attractive and extensive.

This chapter discussed the main findings of this research. It was proposed i) the creation a multidisciplinary team; ii) performing an energy audit, iii) a careful discussion of the existing solutions on a single case basis and iv) a maintenance plan after implementing measures aiming at improving energy performance of heritage buildings.

This discussion merges what was learned both from literature review and from the case studies. By discussing what was done well and what failed in the case studies, it was suggested main ideas to successfully improve the energy performance of heritage buildings. The next chapter presents the conclusions of the thesis.

7 Conclusions

There is a need to understand the importance of preserving the significance of heritage buildings, regarding to its architectural, cultural, historical and aesthetical values as well as to fully understand the conventional or traditional materials and technologies used for the construction of the buildings (Rashid & Ahmad, 2011). The condition and quality of a heritage building are two important aspects to consider as it affects the comfort and productivity of occupants (IEA, 2013). In order to preserve the heritage of the building, retrofitting is mainly carried out in the interior of the building maintaining all of its original exterior wall aspects (Martins & Carlos, 2013). Historic buildings in Europe are usually made of solid masonry walls and single glazed windows. They present two special functioning characteristics: ability to breath and high thermal mass. These features make them more porous and naturally ventilated. This thesis studied how to improve the energy performance of heritage buildings through refurbishment and/or retrofitting processes so that energy use values can be decreased and comfortable temperatures can be maintained to keep up with modern life. A comparative analysis was performed through DMAIC approach. It was concluded that the ReFoMo team can improve its multidisciplinary way of working. It was also found that ReFoMo can benefit from energy audits. Therefore it was proposed how an energy audit should be performed in heritage buildings. This thesis also presents the most widely adopted solutions for refurbishment and/or retrofitting of historic buildings found both in literature and in the case studies.

7.1 Answers to sub-questions

A comparative analysis along with a desk research led to the answers of the four sub-questions of this research:

- 1) What are the important elements of an energy audit to be conducted in buildings?

A combination of testing techniques should be used to both measure and diagnose the energy performance of a building. Various testing techniques are used to investigate building performance. Diagnostic and monitoring tools allowed the analysis of building performance and the discovery of energy saving opportunities. The studied techniques were air tightness test, thermography, heat flux measurement and co-heating test. The air tightness test helps finding the source of draughts and thermography enables the perception of where energy is leaking out of the building. Heat flux measurement compares the in-situ “U” value results with the “U” values calculated from published data or software simulations. The co-heating test describes the thermal calibration of a building.

- 2) How can an energy audit be customized for use into heritage buildings?

An energy audit is the first step to be conducted over retrofitting processes. The energy audit identifies the sources of overconsumption of energy and where energy is being used inefficiently resulting in opportunities to improve energy saving. Every energy audit consists of four steps which are: i) data analysis; ii) On-site survey; iii) Evaluation of energy conservation opportunities and; iv) recommendations. At the same time, there are three key topics where energy savings techniques can be implemented in heritage buildings. These are i) building envelope; ii) electrical appliances and heating systems and; iii) organisational measures.

Building envelope is defined as the part of a building that forms the primary thermal barrier between interior and exterior, also known as the building shell, fabric or enclosure. Electrical appliances and heating systems refer to what consumes energy inside the building. The third key topic refers to organisational measures. This concept deals with behaviour/political changes. During each step, a detailed analysis of the three topics is demanded in the developed layout of an energy audit for heritage buildings. The main advantage of this proposed layout is the attention devoted to the organisational measures, implemented due to protective value interest since heritage buildings are being refurbished and/or retrofitted (see 3.5.1 and 6.2).

3) What refurbishment techniques are available and suitable for heritage buildings?

The answers for the first and second sub-questions provided the required information to build a refurbishment plan of heritage buildings. In section 6.3, solutions were proposed for the most relevant elements in each of the topics within the building envelope, electrical appliances and heating systems and organisational measures.

4) What are the main factors to take into account while aiming at refurbishing heritage buildings?

The availability of technologies is important yet not sufficient. It is also necessary to understand how to apply different technologies and solutions under different circumstances. The building envelope defines the range of materials that can be refurbished and/or retrofitted. Some countries and organisations have specific laws forbidding interventions or replacements due to conservation issues. The functioning of the building, the weather and geographical position are also relevant factors to take into account when considering refurbishment and/or retrofitting processes.

The historic characteristics (i.e. materials of the buildings) restricted the solutions to apply due to the conservation of some elements in the case of the Italian case study. At Fort aan de Klop also due to materials and functioning of the building, it was noted that mechanical ventilation might be unnecessary. The Faculty of Engineering ensured proper ventilation all day long due to orientation. At the “Meter House”, HVAC systems are required since the purpose of refurbishment is to establish a Contemporary Cultural and Communication Centre suitable for large masses and perform various functions.

7.2 Limitations

In the course of the realisation of this thesis, dealing with economical barriers, knowledge/information barriers and opposing regulation came across. The economical factor was not directly related to this thesis but one of the case studies was missing the required funding to carry out the refurbishment plan. The knowledge and information barriers refer to the unavailable information at the time of writing this thesis. A considerable amount of information was required for a successful comparison through DMAIC approach of the three case studies. The three parties approached differently each case, defined different relevant characteristics, measured parameters resorting to distinct methods from each other and also from those referred in literature. The energy audit for heritage buildings contains elements that were not mentioned/analysed in the case studies namely draught proofing, shading devices, electrical appliances, passive heating and cooling. In addition, only the Italian case study performed a thermography within the energy audit (see 5.2.4). It is concluded that miscommunication or lack

of knowledge from other parts involved resulted in data that was incomplete and difficult to compare.

7.3 Suggestion further studies

The importance of planning and setting goals at the beginning of a project thus its results are successful was found fundamental. Taking into consideration the outcomes of this research, the next logical step for future researches aiming at refurbishment and/or retrofitting processes to improve the energy performance of heritage buildings is choosing a sample of buildings in which improving solutions will, in fact, be implemented. The viability of the project should be defined at the beginning. In the future, an energy audit must be performed in all the case studies generating recommendations to improve the energy performance of the elements within of building envelope, electrical appliances and heating systems and organisational measures. Additionally to this, further studies must implement and control the applied solutions in order to verify if the energy performance was improved and (if so) how much.

7.4 General remarks

Each building must be considered not only as an integral part of an urban environment, but also, as an element of construction and management of the territory. Submitting a building to a refurbishment and/or retrofitting processes brings a lot of advantages with it, from keeping original design and materials which have persisted over the times to the fact that converting old historical buildings to new uses is often cheaper than to demolish and rebuild (Harun, 2011; Bullen, 2007). Before finding how to improve energy performance of heritage buildings, an evaluation of each building is required. Based on the findings of this research, refurbishment and/or retrofitting processes in heritage buildings could benefit if i) a multidisciplinary team is created; ii) an energy audit following the layout proposed is performed, iii) the existing solutions for each specific case are carefully analysed and; iv) a maintenance plan is elaborated after implementing measures aiming at control the benefits of the implementation in long terms conditions.

Throughout this thesis it was realised that heritage buildings represent a field of study in constant growth. Investigators are adapting current retrofitting solutions to specific concerns of historic buildings but also developing new products. Even though each heritage building is unique and needs tailored solutions, the guidelines delivered provide a suitable framework for improving the energy performance of these buildings preserving the historical value.

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Appendices

Appendix 1: Fort aan de Klop scenarios

Scenario D: current situation

Heating takes place with gas boilers. The guardhouse is heated by radiators, where the Shed D, E and F are heated through floor heating.

Sustainable measures that are already present:

- Water saving shower heads
- Modern toilets with a dual flush
- Insulation of the sheds (walls, windows and roofs)
- Floor heating in combination with pumps (Low Temperature Heating) for the sheds
- A small kitchen garden with some herbs
- Biological orientation of the restaurant

Scenario C: proposed measures of the energy audit ('MKB advies')

A. Insulation

- Place insulated glass in the guardhouse. HR++ glass is not permitted because of the monumental status; however secondary glazing could be a possibility.

B. Energy generation

- Place some solar panels for generation of electricity

C. Lightning

- Use a motion sensor for lightning
- Replace building site lighting for energy saving light bulbs
- Use LED lightning

D. Smart energy reduction

- Appoint someone who is in charge of the energy use
- Set a time clock on the circulation pumps for heating
- Defrost the freezer regularly
- Set the right temperature of the cooling equipment
- Replace the thermo-regulator of the heating
- Replace separate old freezers and refrigerators for one big cooling device
- Use a gas fired tumble drier (not really more sustainable, but gas heats more efficient than electricity)
- If possible connect the dish washing machine to a hotfill device

Scenario B: a giant stride in energy reduction and energy generation

A. Insulation

- (Scenario C. Secondary glazing for the guardhouse)
- Draught proofing of doors and windows and other connections

B. Energy (generation)

- Place a high number of solar panels (depends on 'Welstand' if this is possible)
- Switch to an energy corporation, which is producing energy from wind-and sun projects, like 'Windunie' and 'Raedthuys'. You can even consider buying a part of a windmill; in this way you generated electricity "yourself".

C. Lightning

- (see scenario C)

D. Smart energy reduction

- (see scenario C)

E. Water& surroundings

- Water playground for children
- A small greenhouse for growing herbs and vegetables for the restaurant in combination with a aquaponics system (closed loop: fish are fed with waste of the kitchen, fish produce humus, plants grow)
- Water tank for watering the area of for washing cars or outside equipment etc.
- Water saving equipment like a flow stop for water taps or (if not already placed) energy saving showerheads. In addition a so called 'shower coach' to raise awareness of the water use under the shower.
- Waste separation system and reuse of compostable waste for the green surroundings (a system of two tanks)

F.1 Heating - Based on existing systems

- Infrared heating for the guardhouse-costs €5.610
- Elga Heating pump (connected to the 65 kW gas boiler for heating) for the sheds-costs €3800
- Solar boiler (connected to the 29 kW (direct) gas fired water boiler)-costs €2.500

F.2 Heating - Based on existing systems

- Gas absorption heating pump for guardhouse and group accommodations
- Gas absorption heating pump (Robur, costs €17.000, 25 kW, energy reduction of 2.988 m³/€1524) combined with the existing gas boilers for peaks (works until -20 degrees)
- Solar boiler (connected to the 29 kW (direct) gas fired water boiler) – costs €2.500

G. Ventilation

- At the moment there is no mechanical ventilation, except for in the sanitary rooms and the kitchen. Is it necessary to implement mechanical ventilation? More research is necessary.
- The entrepreneur did not find it necessary.

Scenario A: Towards autonomy

A. Insulation

- (scenario C& B. Secondary glazing for the guardhouse and draughtproofing)

B. Energy generation

- (Scenario B. Place a high number of solar panels)
- Place a windmill of 15 meters high (in between the urban mill and the big ones) to cover the rest of your electricity consumption. Depends on 'Welstand' if this is possible.

C. Lightning

- (see scenario C)

D. Smart energy reduction

- (See scenario C and B)
- Place an energy manager: see what you use at what time, create awareness

E. Water & surroundings

(See scenario B)

- Reuse of water with a helophytenfilter. Water is used for the toilet

F.1 Heating

- Biomass stove → No gas!
2x biomass stove (palletkachel Calux 48 W) in combination with a buffer tank (120 l).
One biomass stove of 48W can heat up a space of 1000 m³. Total costs: two times 7.500 + 1.200 (buffer) = €16.200. Pallet costs over the year are 3.922 and you gain €5.334 on gas → you gain €1.412 a year.
- Solar boiler (connected to the buffertank)-costs €2.500
- Energy recovery from shower water: 12 showers in shed D, E and F –costs: 12 x 1.200 = €14.400

F.2 Heating

- Vertical heat exchanger (source is the soil) → All electric.
- Costs: €14.000, low temperature heating, can cool in summertime (gain is €1.990, no gas anymore, but 22% more electricity)

G. Ventilation

- At the moment there is no mechanical ventilation, except for in the sanitary rooms and the kitchen. Is it necessary to implement mechanical ventilation? More research is necessary.
- The entrepreneur did not find it necessary.

Appendix 2: How to draw an energy profile without resorting to an auditing company?

An energy audit is the first step to improve the energy performance of a heritage building. It requires experts in the field of energy auditing to comprehensively assess and identify energy upgrades. This evaluation of performance will generate a roadmap of where and how to implement improvements. However, after performing the energy audit and implement the recommendations delivered by the end of the audit, it is possible for users to control the benefits of the refurbishment plan. Table A.2 shows only examples of electrical appliances. The users can then build a similar table for the existing electrical appliances and heating systems. They should indicate the number of equipment, its maximum power, period of use and daily load. The numbers are coloured in grey because they depend on each building so they can be altered. If the building presents more electrical equipment than the equipment in the predefined list, he/she has to complete the table as much as possible. It is important to note that some of the equipment is not used on a daily basis. Therefore, when fulfilling the table, the users must pay attention to that. Then, after realising the energy profile and calculate the daily load, users can calculate the monthly load. Having the monthly load the users of the building can compare values and be critical about the energy use.

Table A.2 – Drawing an energy profile

	Equipment Power Usage				Daily Load (kWh/day)
	Number	Power	Period of use		
Lighting (different technologies of lights)	4	20	3	h/day	0,24
	4	60	2		0,48
Fridge	1	120	10		1,2
Freezer	1	120	10		1,2
Iron	1	1050	1		1,05
Micro-wave	1	900	0,1		0,09
Television	1	60	4		0,24
Vacuum	1	1200	1*week		0,34
Washing machine	1	2200	2*week		0,63
Dish washer	1	1900	2*week		0,54
...					
Totally daily Load					6,01